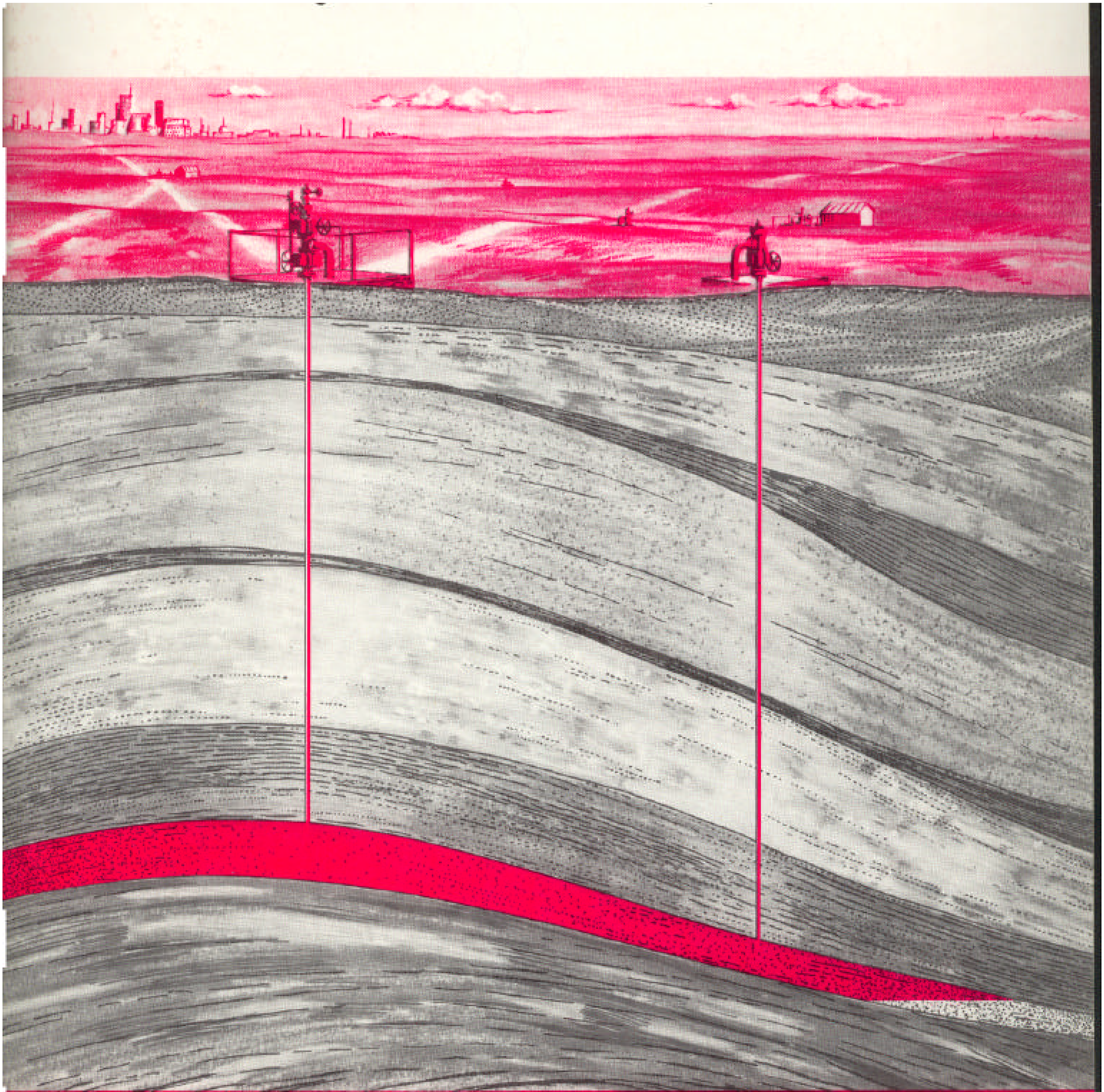
UNDERGROUND STORAGE OF NATURAL GAS IN INDIANA

by T. A. Dawson and G. L. Carpenter



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UNDERGROUND STORAGE OF NATURAL GAS IN INDIANA

by

T. A. Dawson and G. L. Carpenter

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By T. A. Dawson and G. L. Carpenter

ABSTRACT

Underground gas storage is the practical means of making available the increased supplies of natural gas that are needed in Indiana in winter periods of peak demand. To date, 21 gas storage projects providing an estimated storage capacity of 48 billion cubic feet have been initiated. Expansion of storage capacity is anticipated.

Basic geologic factors and availability of subsurface information make establishment of gas storage in the Illinois Basin much easier than in the Michigan Basin or on the Cincinnati Arch. Within the Illinois Basin, storage possibilities are good in the area in which Pennsylvanian and Mississippian rocks contain oil and gas and are excellent in the Geneva Dolomite belt. Throughout Indiana reservoir conditions in Ordovician and Cambrian rocks are adequate for gas storage, but known significant entrapments in these rocks are few.

INTRODUCTION

REASON FOR UNDERGROUND GAS STORAGE

Most gas consumed in the Midwest is transported cross country from the Midcontinent and Gulf Coast by pipelines. Cross-country gas transmission pipelines, with attendant compressor installations and other needs, require vast capital outlays. These costly transmission systems need to be used proficiently if transmission costs are not to become a burdensome part of the price paid for gas by the consumer. They need to be used continuously at near maximum capacity; they need to be used in the summer as well as in the winter. But consumer demand for natural gas is particularly variable in the Midwest because the temperature spread is great and because much of the gas consumed is used for home heating; gas consumption on a cold winter day may be several times as much as on an average day and many times as much as on a warm summer day. Thus the gas industry in the Midwest is confronted with the problem of trying to transmit gas cross country at uniform rates to a consumer public that cannot use it at uniform rates. Three media have been employed to overcome this problem.

Where considerable quantities of natural gas have been developed locally, these may be used to supplement transmission line gas supplies in winter periods of peak demand. Unfortunately, not many areas of the Midwest have appreciable quantities of locally developed natural gas. Indiana has very little, its gas production being only a fraction of a percent of the total gas used.

A second medium that has been used to overcome the problem of uniform gas transmission versus nonuniform gas demand is makeup gas, that is, coke gas and liquified petroleum gas. The use of makeup gas to meet peak winter demands, however, is seldom completely satisfactory because of costs. Not infrequently makeup gas costs more than the price for which it is sold.

The third medium used to overcome the discord between gas supply and gas demand is underground gas storage. Underground gas storage consists of stockpiling cross-country transmission line gas in the proximity of consuming areas when demand is low, primarily in summer months, and using this stockpiled gas when demand is high, primarily in winter months. For much of the Midwest, stockpiling transmission line gas in natural underground reservoirs is the only practical means of overcoming the supply demand discord. In Indiana, with its meager supplies of native natural gas and many urban gas-consuming centers, underground gas storage has become a primary concern of the gas industry.

WHO STORES GAS

Normally two types of gas companies provide service in moving gas from the Midcontinent and Gulf Coast fields to the Midwest consumer. One is the gas transmission company, and the other is the gas distribution company; the services of each are totally complimentary to the other. The transmis-

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1 As of October 10, 1961.

sion company transmits gas cross country and sells it to the distribution company. The distribution company makes delivery through its anastomosing urban lines to the individual consumer.

At first thought, the incentive for establishing gas storage might seem to rest solely with the gas transmitter. This is not true, however, because of the type of agreement commonly made between the transmitter and the distributor. To transmit gas through its costly transmission system at relatively uniform rates, the transmitter will commonly agree to sell gas to the distributor at a reduced price if the distributor will agree to accept gas at a reasonably constant rate throughout the year. With this type of agreement the distributor obviously ends up with excess gas supplies during the summer months, and thus the incentive for establishing gas storage will be as great for the gas distributor as for the gas transmitter. Eight of the nine companies operating storage projects in Indiana are distributors.

Whether gas storage is established by the transmitter or by the distributor does not affect the final result: The proficiency with which costly transmission systems are used is upgraded, and more gas is made available to consuming centers during winter months.

.STATUS OF GAS STORAGE DEVELOPMENT IN INDIANA

In Indiana there are more than two hundred gas-consuming centers (fig. 2). (See also fig. 1 for county names.) Annual consumption is estimated to be more than 225 billion cubic feet. With the expansion of service in existing centers and the addition of new centers each year, annual consumption is going up rapidly. Thus there is a need for large gas storage capacity in Indiana.

Currently gas storage is being developed at a relatively rapid rate (fig. 3), and there are now 21 projects in the State. Large storage capacity has not yet been developed, however, and Indiana lags behind most neighboring states. Total developed storage capacity in Indiana is estimated to be about 48 billion cubic feet. This amount is somewhat more than the estimated 27 billion cubic feet for Kentucky, but it is only a fraction of that estimated for Ohio, Michigan, and Illinois (Pipe Line News, 1961, and. Bell, 1961). Estimates for these states are 437, 465, and 184 billion cubic feet respectively.

Expansion of gas storage in Indiana seems inevitable. Some communities do not have gas service, and many that have service need increased supplies. The most economical means of extending service and increasing supplies is by gas storage. Engineers of both cross-country transmission companies and intrastate distribution companies are concerned daily with programs for expanding gas storage in Indiana.

Realizing that expansion of gas storage was in the public's interest, the Indiana Legislature in 1959 enacted a law permitting application of the principle of eminent domain, in acquiring properties for developing gas storage in subsurface strata (Indiana General Assembly, Acts of 1959, chap. 5, p. 16-19).

Figure 1.-Map of Indiana showing counties.

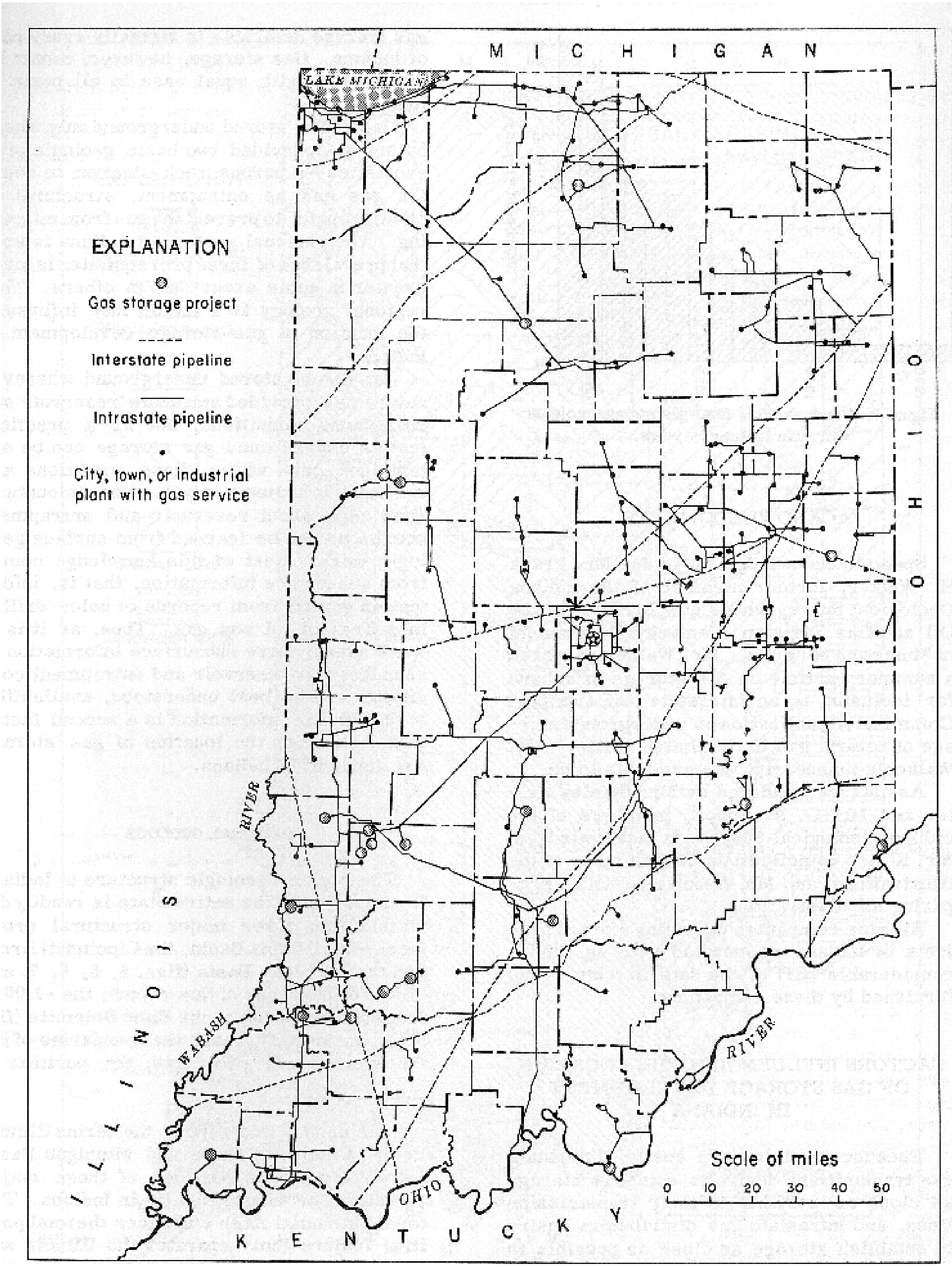

Figure 2. –Map of Indiana showing gas pipelines, storage projects, and consuming centers, Modified after Walker and Rarick, 1960.

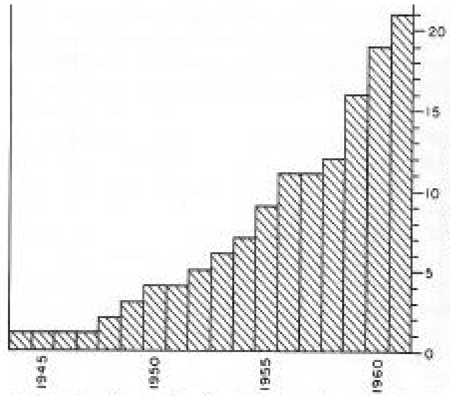

Figure 3.—Graph showing total gas storage projects in Indiana by years.

ACKNOWLEDGMENTS

Special acknowledgment is due Mr. Frank H. Walker, former member of the Indiana Geological Survey who is now Director of the Oil and Gas Division, Kentucky Department of Mines and Minerals. Mr. Walker prepared a summary article on gas storage in Indiana for inclusion in an Interstate Oil Compact Commission publication on underground storage of natural gas in the United States. Mr. Walker's manuscript was available to us.

Assistance rendered by Mr. Stanley Keller and Mr. G. A. Abbott, members of the Indiana Geological Survey, is acknowledged. Mr. Keller compiled data used in some of the illustrations, and Mr. Abbott assisted in preparing all illustrations.

All nine companies operating storage projects in Indiana cooperated with us, and a considerable part of the data in table 2 was furnished by these companies.

FACTORS INFLUENCING THE LOCATION OF GAS STORAGE DEVELOPMENT IN INDIANA

Because pipelines are costly, interstate gas transmitters desire to establish storage as close as possible to their transmission lines, and intrastate gas distributors desire to establish storage as close as possible to the consuming centers they serve. Location of interstate transmission lines and distribution of consuming centers (fig. 2) make gas storage desirable in virtually every part of Indiana. Gas storage, however, cannot be established with equal ease in all parts of Indiana.

Gas can be stored underground only where nature has provided two basic geologic prerequisites--a porous rock stratum to house the gas and an entrapment, structural or stratigraphic, to prevent the gas f rom migrating. The regional geology of Indiana is such that prevalence of these prerequisites is much greater in some areas than in others. Thus regional geology is a factor that influences the location of gas storage development in Indiana.

Gas can be stored underground wherever nature has provided adequate reservoir and entrapment conditions, but as a practical matter underground gas storage can be established only where these conditions are evident. In Indiana only limited amounts of knowledge about reservoir and entrapment conditions can be learned from surface geologic work. Most of this knowledge comes from subsurface information, that is, information gained from records of holes drilled in search of oil and gas. Thus, as it is in those areas where subsurface information is abundant that reservoir and entrapment conditions will be best understood, availability of subsurface information is a second factor that influences the location of gas storage development in Indiana.

REGIONAL GEOLOGY

The regional geologic structure of Indiana is simple, and the entire State is readily divisible into three major structural provinces- -the Illinois Basin, the Cincinnati Arch, and the Michigan Basin (figs. 4, 5, 6, 7, and 8).[2] For purposes of this report, the - 1,600foot contour on top of the Knox Dolomite (fig. 5) is considered to mark the boundaries of the three structural provinces; the position of

[2] As used in this report, the terms Illinois Basin, Cincinnati Arch, and Michigan Basin refer only to the portions of these major structural provinces that lie in Indiana. The term Cincinnati Arch embraces the total positive feature that separates the Illinois and Michigan Basins. For the northwestern part of this feature, the term Kankakee Arch has sometimes been used by others.

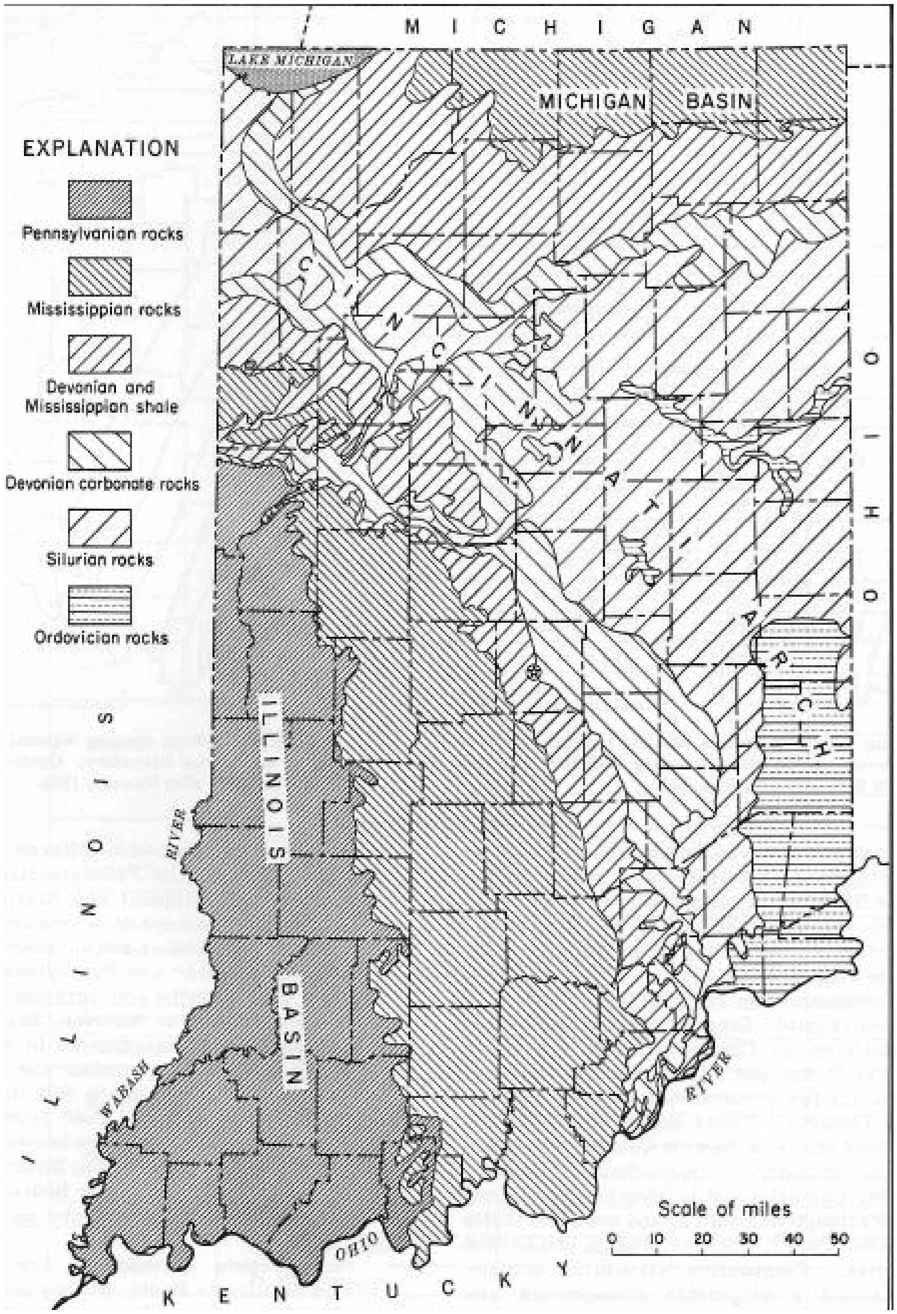

Figure 4-Generalized bedrock map of Indiana. Modified after Patton, 1955.

Figure 5.-Map of Indiana showing regional structure on top of the Knox Dolomite. Contour interval 500 feet. After Dawson, 1960.

Figure 6.-Map of Indiana showing regional structure on top of the Trenton Limestone. Contour interval 500 feet. Modified after Dawson, 1952.

this contour is very closely approximated by the position of the -500-foot contour on top of the Trenton Limestone (fig. 6) and is generally approximated by the position of the +500-foot contour on top of the Devonian carbonate sequence (fig. 7).

Entrapments.-The regional dip of strata in Indiana is mild. Dips range from 5 to 10 feet per mile on the Cincinnati Arch to as much as 60 or 70 feet per mile in the Illinois Basin. There are few pronounced diastrophic structural features. Those known consist of the Kentland Dome in Newton County, which has been described as a cryptovolcanic structure, the Mt. Carmel Fault in Monroe, Lawrence, and Washington Counties, and unnamed faults in Cass, Perry, Spencer, Posey, and Gibson Counties. Compaction structural entrapments and stratigraphic entrapments are much more common than diastrophic structural entrapments.

Compaction (draped) structural entrapments are associated with differential compaction of rocks in the Pennsylvanian, Chester (upper Mississippian) and Silurian (table 1). Differential compaction between lenticular quartz sand bodies and surrounding clay muds in the Chester and Pennsylvanian, and between reef growths and surrounding lime and clay muds in the Silurian, has induced draped structural entrapments in overlying porous beds. Pennsylvanian and Chester rocks are present in Indiana only in the Illinois Basin (fig. 4). And reef growths with induced draped structure are known in Indiana only in the. Illinois Basin; Silurian reefs on the Cincinnati Arch lack bedrock cover and in the Michigan Basin are an unknown quantity.

Stratigraphic entrapments are common only in the Illinois Basin, as they are limited primarily to Pennsylvanian and Chester rocks. In the Pennsylvanian and Chester, lenses of porous quartz sand are commonly

Table I.-*Stratigraphic position of natural gas reservoirs and gas storage reservoirs in Indiana*

System	Series	Formation or group	Lithology*	Natural	Gas
Pennsylvanian	Conernaugh	Undifferentiated	sh, as, ls, coal	x	
	Allegheny	Undifferentiated	sh, as, ls, coal	x	x
	Pottsville	Undifferentiated	sh, as, coal	x	
Mississippian	Chester	Kinkaid Limestone	ls, sh		
		Degonia Sandstone	as, sh		
		Clore Limestone	ls, ss, sh		
		Palestine Sandstone	as, sh	x	
		Menard Limestone	ls, sh		
		Waltersburg Sandstone	as, sh		
		Vienna Limestone	ls, sh		
		Tar Springs Formation	as, sh	x	
		Glen Dean Limestone	ls, sh		
		Hardinsburg Formation	as, sh	x	
		Golconda Limestone	ls, sh		
		Big Clifty (Jackson) Formation	as, sh	x	
		Beech Creek (Barlow) Limestone	ls		
		Cypress Formation	as, sh	x	x
		Paint Creek Formation	ls, as, sh	x	
		Bethel Formation	as, sh	x	x
		Renault Formation	ls, as, sh	x	
		Aux Vases Formation	ls, sh, as	x	
	Meramec	Ste. Genvieve Limestone	ls, sh, as	x	
		St. Louis Limestone	ls, sh		
		Salem Limestone	ls	x	
		Harrodsburg Limestone	ls, sh		
	Osage	Borden Group	sit, sh, ls, as		
	Kinderhook	Rockford Limestone	ls		
Devonian	Undifferentiated	New Albany Shale	sh	x	
		North Vernon Limestone	ls, dol	x	x
		Jeffersonville Limestone	ls, dol		
		Geneva Dolomite	dol	x	x
Silurian	Undifferentiated	Undifferentiated	ls, dol, sh		
Ordovician	Cincinnatian	Undifferentiated	sh. ls		
	Mohawkian	Trenton Limestone; Cynthiana Formation	ls, dol	x	x
		Black River Limestone	ls, dol	x	
	Chazyan	Joachim Dolomite	dol		
		St. Peter Sandstone	as		x
	Canadian	Knox Dolomite	dol, as		

* dol -- dolomite Is -- limestone as -- sandstone sh -- shale s1t -- siltstone

Figure 7.-Map of Indiana showing regional -structure on top of the Devonian carbonate sequence. Generalized limit of mapped horizon shown by dashed line. Contour interval 500 feet. Compiled by Arthur P. Pinsak, 1961.

Figure 8.-Map of Indiana showing regional structure on top of the Cypress Formation. Generalized limit of mapped horizon shown by dashed line. Contour interval 500 feet. Compiled by Dan M. Sullivan, 1961.

wholly encased in impervious shale beds. Although the oil and gas of the Trenton Field are trapped under stratigraphic conditions, the principal entrapment is of regional proportions and therefore probably of no value for gas storage.

Porous strata. - Many more porous strata in which gas can be stored when favorable entrapment conditions exist occur in the Illinois Basin than on the Cincinnati Arch or in the Michigan Basin. There are literally dozens of porous sandstone units in the Pennsylvanian and Chester. Natural accumulations of oil and gas occur in some Pennsylvanian stratigraphic units containing sand and in all Chester units containing sand. In addition, all carbonate stratigraphic units of Meramec (middle Mississippian) age are porous in restricted areas and all have been found to contain oil and gas. Meramec rocks (table 1), as the Pennsylvanian and Chester, are restricted to the Illinois Basin.

Devonian and Silurian carbonate strata occur at depth in both the Illinois and Michigan Basins. Reservoir characteristics of these rocks are not well understood in the Michigan Basin or in parts of the Illinois Basin. But in an east-west oriented belt within the Illinois Basin, where there has been extensive drilling for Devonian oil and gas, the Devonian strata are well understood. In this belt, dolomites in the Devonian are as porous and permeable as any rocks in Indiana. The thickest and most persistent of these dolomite strata is the basal Devonian stratigraphic unit known as the Geneva Dolomite (fig. 9).

The Trenton Limestone and sub-Trenton rock units (table 1) occur with bedrock cover throughout virtually all of Indiana. Forma-

Figure 9.-Map showing outcrop and subsurface distribution of the Geneva Dolomite in Indiana.

tions within this rock section that may reasonably be considered as potential gas storage reservoirs are the Trenton Limestone, St. Peter Sandstone, Knox Dolomite, Eau Claire Formation, and Mt. Simon Sandstone. Considered as a whole, the reservoir characteristics of these formations Are somewhat better on parts of the Cincinnati Arch and in parts of the Michigan Basin than in the Illinois Basin, although to some degree each formation must be considered as a potential storage reservoir in some parts of all three provinces.

It can readily be concluded that the basic geologic prerequisites for establishing underground gas storage, namely, entrapments and porous strata, are more prevalent in the Illinois Basin than in the other two regional provinces. Virtually all significant compaction structures, most of the known stratigraphic entrapments, all porous Pennsylvanian and Mississippian rocks, and the highly porous and permeable Devonian dolomites occur in the Illinois Basin.

AVAILABILITY OF SUBSURFACE INFORMATION

Subsurface information is of paramount importance in interpreting structure and stratigraphy in Indiana. Possibilities for determining structural conditions favorable for gas storage by surface mapping are very limited. The northern two thirds of the State is blanketed by glacial drift, and in many areas of the southern part of the State, efforts to map structure in detail are frustrated by lack of exposures in areas of low relief. Furthermore, many of the compaction structural features of the Illinois Basin are not evidenced, or are only vaguely suggested, in the surface bedrock.

Within Indiana recognition of most compaction structural entrapments, some diastrophic structural entrapments, and all stratigraphic entrapments is possible only through the medium of subsurface information. In addition, knowledge of the porosity and permeability characteristics of reservoir strata is always enhanced by subsurface data, and many times these characteristics can be understood only from subsurface data. Thus geologic conditions under which gas can be stored will be most evident in those areas of Indiana for which there are plentiful subsurface data.

Intense drilling for oil and gas has taken place in two areas of Indiana--M the east-central part of the State in the Trenton Field on the Cincinnati Arch and (2) the southwestern part of the State in large areas of the Illinois Basin. Drilling in the Trenton Field took place many years ago; the drilling records are very incomplete and very limited in quality (mostly drillers logs), and many of the records are unusable because of inaccuracies. On the other hand, drilling in the Illinois Basin is recent, and excellent records, such as drillers logs, samples, electric logs, and drilling-time logs, are available for interpreting subsurface geologic conditions. As it is only in the Illinois Basin that good quality subsurface information in large quantity is available, geologic conditions under which gas can be stored are more readily determinable in that structural province than in the other two structural provinces.

In summation, both regional geology and available subsurface information favor gas storage development in the Illinois Basin.

These factors have influenced the location of gas storage development in Indiana to date; 16 of the total 21 storage projects are in the Illinois Basin (figs. 4, 5, 6, and 10). They undoubtedly will also influence the location of future gas storage development in Indiana.

The gas storer in the Illinois Basin commonly has only to study available subsurface data to select sites favorable for gas storage. But the gas storer situated on the Cincinnati Arch or in the Michigan Basin will commonly have to conduct costly exploration programs to find sites favorable for gas storage, and basic geologic factors indicate that he will be conducting these programs in areas where entrapments (particularly compaction 'structures and stratigraphic traps) and porous strata are relatively few compared to entrapments and porous strata in the Illinois Basin.

GAS STORAGE PROJECTS IN INDIANA

Some of Indiana's 21 gas storage projects are new (fig. 3 and table 2). In some of these gas injection has not yet been initiated; in others, though gas injection has been started, development is considered to be in an experimental or testing stage. Inclusion in this report of a newly started gas storage project does not imply that a successful gas storage operation has been established. For purposes of this report all areas for which gas storage permits have been issued are considered as gas storage projects.

We estimate that total gas storage capacity in Indiana will be about 48 billion cubic feet when projects in an experimental or testing stage are put into operation. Total working capacity (storage capacity less cushion gas) will be about 27 billion cubic feet, and total maximum daily deliverability will be about 450,000 Mcf (thousand cubic feet).

ALFORD PROJECT

The Alford project (pl. 1, fig. 10, and table 2) in Pike County is owned by the Texas Gas Transmission Corp. Storage is in Cypress sandstone in a stratigraphic entrapment. The storage reservoir, which is a depleted natural gas reservoir, averages 20 feet in thickness and is at a depth of 1, 050 feet. Porosity averages 12 percent, and permeability averages 59 millidarcies.

Forty-three wells are operated, thirty-nine for injection and extraction of gas and four for observation. Thirty-nine old holes were cleaned out and plugged during development. Total storage capacity is 2,469,300 Mcf, working storage capacity is 969,300 Mcf, and maximum daily deliverability is 40,000 Mcf.

Alford, which is the third oldest storage project in Indiana, was placed in operation in 1951.

GIRO EAST PROJECT

The Giro East project (pl. 1, fig. 10, and table 2) in Pike County is owned by the Texas Gas Transmission Corp. The storage reservoir is Cypress sandstone in which there was a natural accumulation of gas. Entrapment is stratigraphic. Depth of the reservoir is 1,380 feet, and average thickness is 30 feet.

Twelve wells have been completed for injection and extraction of gas. Two old holes have been cleaned out and plugged, and four new holes have been abandoned and plugged. No gas has been stored to date.

GLENDALE NORTH PROJECT

The Glendale North project (pl. 1, fig. 10, and table 2) in Daviess County is owned by the Hoosier Pipe Line Corp. Storage is in Cypress sandstone in a stratigraphic entrapment. The storage reservoir is a depleted natural gas reservoir. Depth to the reservoir is 740 feet, and average thickness is 10 feet.

Five wells are operated, four for injection and extraction of gas and one for observation. All are converted gas producers. Working storage capacity is 200,000 Mcf.

GREEN HILL PROJECT

The Green Hill project (pl. 1, fig. 10, and table 2) in Warren County is owned by the Indiana Gas and Water Co. Storage is in dolomite near the top of the Silurian. Entrapment is structural, probably due to a Silurian reef; that is, structural closure has probably been induced by differential compaction between underlying reef and nonreef rocks. The storage reservoir is an aquifer, has an average thickness of 15 feet, and is at a depth of 410 feet.

Table 2.–*Statistical summary of gas storage projects in Indiana*

PROJECT[1]	OPERATOR	LOCATION		OPERATIONAL DATES		RESERVOIR DATA													
		County	Township and range[2]	Development initiated	Storage initiated[3]	Type	Entrapment	Stratigraphic unit	Lithology	Average porosity (percent)	Average permeability (millidarcies)	Approximate depth (feet)	Approximate thickness (feet)	Approximate area (acres)	Number of wells	Total capacity (Mcf)	Working capacity (Mcf)	Maximum daily deliverability (Mcf)	Annual throughput (Mcf)
Alford	Texas Gas Transmission Corp.	Pike	1N-7W	1949	1951*	Natural gas	Stratigraphic	Cypress	Sandstone	12*	59*	1,050	20*	1,270*	43	2,469,300*	969,300*	40,000*	-----
Giro East	Texas Gas Transmission Corp.	Pike	1N-9W	1959	-----	Natural gas	Stratigraphic	Cypress	Sandstone	-----	-----	1,380	30	308*	12	-----	-----	-----	-----
Glendale North	Hoosier Pipe Line Corp.	Daviess	2N-6W	1955	1955*	Natural gas	Stratigraphic	Cypress	Sandstone	-----	-----	740	10	200	5	-----	200,000*	-----	-----
Green Hill	Indiana Gas and Water Co.	Warren	22N-6W	1961	1961*	Aquifer	Structural	Silurian	Dolomite	-----	-----	410	15	250	4	-----	-----	-----	-----
Greensburg	Indiana Gas and Water Co.	Decatur	9N-9E and 10E 10N-9E and 10E	1950	1950*	Natural gas	Stratigraphic	Trenton	Limestone	4*	-----	880	15*	3,000	87	1,000,000*	400,000*	1,600*	108,336*
Howesville	Citizens Gas and Coke Utility	Greene	8N-7W	1959	1961*	Natural gas	Structural	Devonian (undifferentiated North Vernon and Jeffersonville)	Dolomite	16.6*	40-140*	1,720	35	570*	11	5,000,000*	3,200,000*	25,000*	-----
Laconia	Ohio Valley Transmission Corp.	Harrison	6S-4E	1948	1953*	Natural gas	Structural	Devonian (undifferentiated North Vernon and Jeffer-sonville) and Silurian	Dolomite	15*	500*	460-650	15*	862*	34	1,535,289*	640,918*	-----	-----
Lawrenceburg	Lawrenceburg Gas Co.	Dearborn	5N-1W	1954*	1956*	Natural gas	Stratigraphic?	Cynthiana	Limestone	-----	-----	250	20	60	3	15,000*	15,000*	1,500*	100,000*
Leesville	Texas Gas Transmission Corp.	Lawrence	5N-2E	1956	1959*	Aquifer	Structural	Devonian (Geneva)	Dolomite	-----	-----	750-850	20	6,200*	16	2,600,000*	-----	10,000*	-----
Linkville	Northern Indiana Public Service Co.	Marshall	34N-2E	1961	-----	Aquifer	Structural?	Silurian	Dolomite	-----	-----	465	15	120	3	-----	-----	-----	-----
Linton	Citizens Gas and Coke Utility	Greene	7N-7W	1959	-----	Natural gas	Structural	Devonian (undifferentiated North Vernon and Jeffersonville)	Dolomite	11.6*	2.5-25*	1,950	40	340*	12	3,460,000*	2,500,000*	-----	-----
Lonetree	Citizens Gas and Coke Utility	Greene	8N-6W and 7W	1959	1959*	Natural gas	Structural	Devonian (undifferentiated North Vernon and Jeffersonville)	Dolomite	-----	-----	1,750	40	550	10	-----	-----	-----	-----
Loogootee	Hoosier Pipe Line Corp.	Daviess	3N-5W	1955	1955*	Natural gas	Stratigraphic	Bethel	Sandstone	-----	-----	560	20	100	4	-----	105,000*	-----	-----
Oaktown	Texas Gas Transmission Corp.	Knox	5N-10W	1944	1944*	Natural gas	Stratigraphic	Allegheny	Sandstone	-----	-----	610	8*	1,480*	29	1,031,200*	610,710*	9,000*	-----
Oliver	Southern Indiana Gas and Electric Co.	Posey	5S-13W 6S-13W	1952*	1954*	Natural gas	Stratigraphic	Allegheny	Sandstone	18.2*	119*	780	10	1,168*	45	2,900,000*	1,041,000*	40,000*	1,309,735*
Royal Center	Northern Indiana Public Service Co.	Cass Fulton	28N-1E and 1W 29N-1E	1960	1961*	Aquifer	Structural	St. Peter	Sandstone	17*	400*	1,350	23*	10,000*	20	2,000,000-10,000,000*	1,000,000-8,000,000*	20,000-80,000*	-----
Unionport	Central Indiana Gas Co.	Randolph	19N-13E	1960	-----	Natural gas	Stratigraphic?	Trenton	Limestone	6*	1*	1,060	15*	2,560*	-----	-----	-----	-----	-----
Unionville	Indiana Gas and Water Co.	Monroe	9N-1E	1953	1954*	Natural gas	Structural	Devonian (undifferentiated North Vernon and Jeffersonville)	Dolomite	6*	-----	800	7*	8,000*	22	2,470,000*	984,580*	23,000*	984,580*
				1960	1961*	Aquifer	Structural	Devonian (Geneva)	Dolomite	-----	-----	890	40	-----	-----	-----	-----	-----	-----
Westpoint	Indiana Gas and Water Co.	Tippecanoe	22N-5W and 6W	1956	1957*	Aquifer	Structural	Devonian (undifferentiated North Vernon and Jeffersonville)	Limestone	8*	-----	400	12*	1,500*	27	650,000*	200,000*	7,500*	488,000*
Wilfred	Texas Gas Transmission Corp.	Sullivan	9N-8W	1958	1959*	Oil	Structural	Devonian (Geneva)	Dolomite	12.3*	84*	2,030	30	1,110*	18	2,400,000*	1,200,000*	30,000*	-----
Worthington	Citizens Gas and Coke Utility	Greene	7N-5W 8N-5W	1960	1961*	Natural gas	Structural	Devonian (undifferentiated North Vernon and Jeffersonville)	Dolomite	18.1*	18.2-35.4*	1,420	35	2,000	28	9,000,000*	-----	-----	-----

[1] For maps of projects, see plate 1. For locations of projects within the State, see figure 9.

[2] The Lawrenceburg project is located with reference to the First Principal Meridian (southeastern Indiana). All other projects are located with reference to the Second Principal Meridian.

[3] Dashed lines indicate that no gas has been stored to date.

*Data furnished by operator.

Figure 10.-Map of Indiana showing stratigraphic position and ownership or gas storage projects.

Four wells have been completed for injection and extraction of gas, and a permit has been issued for completion of a fifth well. Only a small amount of gas has been injected to date, and the project is classed as experimental.

GREENSBURG PROJECT

The Greensburg project (pl. 1, fig. 10, and table 2) in Decatur County is owned by the Indiana Gas and Water Co. Storage is in the Trenton Limestone in a stratigraphic entrapment; the stratigraphic nature of the entrapment is deduced, as there is virtually no structural closure on top of the Trenton Limestone. The storage reservoir, a depleted natural gas reservoir, averages 15 feet in thickness and is at a depth of 880 feet; its porosity averages 4 percent.

Eighty-seven wells are operated, sixty for injection and extraction of gas and twenty-seven for observation. All were originally drilled for gas production. Total storage capacity, working storage capacity, and maximum daily deliverability are 1,000,000 Mcf, 400,000 Mcf, and 1,600 Mcf respectively.

Greensburg is the second oldest gas storage project in Indiana. Storage operations were initiated in 1950.

HOWESVILLE PROJECT

The Howesville project (pl. 1, fig. 10, and table 2) in Greene County is owned by the Citizens Gas and Coke Utility. Storage is in Devonian dolomite in the lower part of the undifferentiated North Vernon and Jeffersonville Limestones. Entrapment is structural and is due to an underlying Silurian reef; that is, structural closure in Devonian beds has been induced by differential compaction between reef and nonreef rocks in the Silurian. The storage reservoir, a natural gas reservoir, is at a depth of 1,720 feet and is 35 feet thick. Porosity averages 16. 6 percent, and permeability ranges from 40 to 140 millidarcies.

Eleven wells are operated, five for injection and extraction of gas and six for observation. Total storage capacity is 5,000,000 Mcf, working storage capacity is 3,200,000 Mcf, and daily deliverability is 25,000 Mcf.

The deliverability potential of individual wells in Howesville is extremely high--about 15 to 20 million cubic feet per day--and is not commensurate with the recorded reservoir permeability. The vuggy character of the Devonian dolomite reservoir probably explains the high deliverability of wells. Actual reservoir permeability is probably several times the recorded permeability of 40 to 140 millidarcies.

The reservoir thickness of 35 feet represents that part of the Devonian dolomite section mechanically opened in storage wells. Effective reservoir thickness is probably much greater because the vuggy dolomite opened in storage wells is underlain by the vuggy Geneva Dolomite, which is underlain by vuggy Silurian dolomite. Effective reservoir thickness is probably limited only by structural closure, which is about 85 feet.

LACONIA PROJECT

The Laconia project (pl. 1, fig. 10, and table 2) in Harrison County is owned by the Ohio Valley Transmission Corp., subsidiary of the Louisville Gas and Electric Co. Storage is in Devonian and Silurian dolomite in a structural entrapment. The storage reservoir is a depleted natural gas reservoir and averages 15 feet in thickness. Depth to the reservoir ranges from 460 to 650 feet; variation in depth is due principally to rugged terrain. Porosity averages 15 percent, and permeability averages 500 millidarcies.

Thirty-four wells are operated, thirty-one for injection and extraction of gas and three for observation. Permits have been issued for the completion of two additional wells. Total storage capacity is 1,535,289 Mcf, and working storage capacity is 640,918 Mcf.

The Laconia project is contiguous with the Doe Run gas storage project in Meade County, Ky., which is also operated by the Louisville Gas and Electric Co. Figures that represent the combined storage capacity of these two contiguous storage areas have appeared in print. The figures presented here, however, pertain only to the Laconia storage project.

The Devonian and Silurian carbonate section in the area of the Laconia project is anomalously thin. The Devonian part of the section, which is dolomite as opposed to limestone in surrounding areas, is particularly thin. It is only 20 feet thick in some places and may very well be even thinner in others. This Devonian dolomite, which is undifferentiated North Vernon and Jeffersonville in age, constitutes the principal part of the storage reservoir, but some storage wells penetrate the Silurian rocks. Thus the storage reservoir has been designated as Devonian and Silurian in age.

.LAWRENCEBURG PROJECT

The Lawrenceburg project (pl. 1, fig. 10, and table 2) in Dearborn County is owned by the Lawrenceburg Gas Co. Storage is in the Cynthiana Formation. Although lack of marker beds precludes a structural interpretation, entrapment is presumed to be stratigraphic. The storage reservoir, a natural gas reservoir, is approximately 20 feet thick and is at a depth of 250 feet.

Three wells are operated for injection and extraction of gas. Total storage capacity and working storage capacity are each 15,000 Mcf, and maximum daily deliverability is 1,500 Mcf.

The Cynthiana Formation consists of alternating limestone and black shale beds. Gas occurrence in this formation in southeastern Indiana and northern Kentucky is common. Data at hand indicate that gas occurs in the limestone beds and not in the shale beds. Because simple monoclinal dips prevail throughout the area of southeastern Indiana and northern Kentucky, the gas accumulations in the Cynthiana, limestones are presumed to be stratigraphic. The Cynthiana limestones may very well be lenticular.

LEESVILLE PROJECT

The Leesville project (pl. 1, fig. 10, and table 2) in Lawrence County is owned by the Texas Gas Transmission Corp. Storage is in the Geneva Dolomite (basal Devonian), and entrapment is structural. The storage reservoir is an aquifer, averages 20 feet in thickness, and is at a depth of 750 to 850 feet. Variation in depth is due primarily to rough terrain.

Sixteen wells are operated, nine for injection and extraction of gas and seven for observation. Permits for drilling two new storage wells have been issued. During development eight old holes were cleaned out and plugged and three structure test wells were drilled and plugged. Total storage capacity is 2,600,000 Mcf, and maximum daily deliverability is 10,000 Mcf.

The Leesville project is on the Dennison Dome of the Leesville Anticline (Melhorn and Smith, 1959).

LINKVILLE PROJECT

The Linkville project (pl. 1, fig. 10, and table 2) in Marshall County is owned by the Northern Indiana Public Service Co. Storage is in Silurian dolomite, and entrapment is interpolated f rom meager data as being structural. The storage reservoir is an aquifer, is at a depth of 465 feet, and is 15 feet thick.

Three wells have been completed, one for injection and extraction of gas and two for observation. Forty-eight test holes for stratigraphic and structural information have also been drilled. To date no gas has been stored.

Very little data on wells drilled in Linkville have been released by the operator. But scattered control from the few old holes drilled in the area suggests anomalous structure, and thus it is conjectured that entrapment at the Linkville project is structural.

LINTON PROJECT

The Linton project (pl. 1, fig. 10, and table 2) in Greene County is owned by the Citizens Gas and Coke Utility. Storage is in Devonian dolomite in the lower part of the undifferentiated North Vernon and Jeffersonville Limestones, and entrapmentis structural. Structure is due to an underlying Silurian pinnacle reef. The storage reservoir, which is 40 feet thick and is at a depth of 1,950 feet, is a natural gas reservoir. Porosity averages 11. 6 percent, and recorded permeability ranges from 2. 5 to 25 millidarcies.

Twelve wells have been completed, five for injection and extraction of gas and seven for observation. The operator rates total storage capacity at 3, 460, 000 Mcf and working storage capacity at 2, 500, 000 Mcf. No gas has been stored to date, but the operator plans to initiate gas injection in the near future.

Structural and reservoir conditions at Linton are very similar to those at Howesville, and points made about the high deliverability of wells and effective reservoir thickness at Howesville are probably applicable to Linton. Structural closure at Linton is approximately 130 feet.

LONETREE PROJECT

The Lonetree project (pl. 1, fig. 10, and table 2) in Greene County is near Howesville and Linton and like them is owned by the Citizens Gas and Coke Utility. As at Howesville and Linton, storage is in a natural gas reservoir in Devonian dolomite in the lower part of the undifferentiated North Vernon and Jeffersonville Limestones, and entrapment is due to structure formed over an underlying Silurian reef. The storage reservoir is 40 feet thick and is at a depth of 1,750 feet. Defined structural closure is approximately 60 feet.

Ten wells have been completed, three for injection and extraction of gas and seven for observation. A small amount of gas was injected at Lonetree in 1959. For the present, storage operations have been suspended.

LOOGOOTEE PROJECT

The Loogootee project (pl. 1, fig. 10, and table 2) in Daviess County is owned by the Hoosier Pipe Line Corp. Storage is in Bethel sandstone, and entrapment is stratigraphic. The storage reservoir, a depleted natural gas reservoir, averages 20 feet in thickness and is at a depth of 560 feet.

Four wells are operated for injection and extraction of gas, and all of them are converted gas producers. Working storage capacity is 105,000 Mcf.

OAKTOWN PROJECT

The Oaktown project (pl. 1, fig. 10, and table 2) in Knox County is owned by the Texas Gas Transmission Corp. Storage is in a depleted natural gas reservoir in sandstone in the lower part of the Allegheny Series. Entrapment is stratigraphic. The storage reservoir averages 8 feet in thickness and is at a depth of 610 feet.

Twenty-nine wells are operated, twenty-four for injection and extraction of gas and five for observation. Twenty-two old holes were cleaned out and plugged during development. Total storage capacity is 1,031,200 Mcf, working storage capacity is 610,710 Mcf, and maximum daily deliverability is 9,000 Mcf.

We believe that all injection-extraction wells in Oaktown may not be completed in the same sandstone body. Records indicate that the three injection-extraction wells at the south edge of the project are completed in a sandstone approximately 25 feet below Coal III, whereas the injection-extraction wells in the remainder of the project are completed in a sandstone approximately 55 feet below Coal III.

Oaktown is the oldest gas storage project in Indiana. Storage operations were initiated in 1944 by the Kentucky Natural Gas Corp., forerunner of the Texas Gas Transmission Corp.

OLIVER PROJECT

The Oliver project (pl. 1, fig. 10, and table 2) in Posey County is owned by the Southern Indiana Gas and Electric Co. As at Oaktown, storage is in sandstone in the lower part of the Allegheny Series, and entrapment is stratigraphic. The storage reservoir, a depleted natural gas reservoir, averages 10 feet in thickness and is at a depth of 780 feet. Porosity averages 18.2 percent, and permeability averages 119 milldarcies.

Forty-five wells are operated, all for injection and extraction of gas; one old hole was cleaned out and plugged and seven dry holes were abandoned and plugged.

Total storage capacity is 2,900,000 Mcf, working storage capacity is 1,041,000 Mcf, and maximum daily deliverability is 40,000 Mcf.

Three of the wells at Oliver are completed in a small sandstone reservoir approximately 50 feet above the main storage reservoir. This small reservoir is used as a reserve source of gas to meet abnormally high peak demands. Maintained normally at maximum pressure, it provides short-term high deliverability.

ROYAL CENTER PROJECT

The Royal Center project (pl. 1, fig. 10, and table 2) in Cass and Fulton Counties is owned by the Northern Indiana Public Service Co. Storage is in the St. Peter Sandstone in a structural entrapment. The storage reservoir, which is an aquifer, averages 23 feet in thickness and is at a depth of 1, 350 feet. Porosity is 17 percent, and permeability averages 400 millidarcies.

Twenty wells are operated, twelve for injection and extraction of gas and eight for observation. Twenty- four additional holes have been drilled for stratigraphic and structural information. Total storage capacity is estimated to be between 2,000,000 and 10,000,000 Mcf, and working storage capacity is estimated to be between 1,000,000 and 8,000, 000 Mcf. Maximum daily deliverability is estimated at 20, 000 Mcf to 80,000 Mcf.

The structural feature in which storage is effected at Royal Center is a large anticline, bounded on the southeast by a fault which has displacement of about 100 feet. These major diastrophic structural features were first revealed by the exploration and development drilling connected with the Royal Center gas storage project.

UNIONPORT PROJECT

The Unionport project (pl. 1, fig. 10, and table 2) in Randolph County is owned by the Central Indiana Gas Co. Storage is in the Trenton Limestone. The storage reservoir, which contained some natural gas, is 15 feet thick and is at a depth of 1, 060 feet. Porosity is 6 percent, and permeability is 1 millidarcy. Type of entrapment is not known but is guessed to be stratigraphic.

No gas has been stored to date. Twenty test holes have been drilled for stratigraphic and structural information, and permits have been issued for completion of four gas storage wells.

As yet, little data have been released on the newly drilled holes in Unionport, and thus a structural interpretation has not been made. We speculate, however, that entrapment conditions are not structural, but stratigraphic. This speculation is made because most gas accumulations in the Trenton Limestone in eastern Indiana are due to lateral changes in permeability rather than to structural closure.

The operator at Unionport has indicated that gas storage may be attempted in the Knox Dolomite should the low porosity and permeability of the Trenton preclude effective storage.

UNIONVILLE PROJECT

The Unionville project (pl. 1, fig. 10, and table 2) in Monroe County is owned by the Indiana Gas and Water Co. Entrapment conditions are structural. Two reservoirs are being operated.

In the upper reservoir storage is in lenses of Devonian dolomite in the undifferentiated North Vernon and Jeffersonville Limestones at a depth of 800 feet. The storage reservoir is a depleted natural gas reservoir and is 7 feet thick (net thickness). Porosity is 6 percent. Twenty-two wells are operated, twelve for gas injection and extraction and ten for observation. Total storage capacity, working storage capacity, and maximum daily deliverability are 2,470,000 Mcf, 984,580 Mcf, and 23,000 Mcf respectively.

In the lower reservoir storage is in the Geneva Dolomite (basal Devonian) and is at a depth of 890 feet. This reservoir is an aquifer and is 40 feet thick. Nine permits that authorize the operator to drill wells into the Geneva Dolomite have been issued. Some of these wells have been completed, and gas injection has been initiated. All active operations shown on the Unionville map of plate 1 indicate wells scheduled to be drilled to the Geneva.

The Unionville project is on the Unionville Dome of the Leesville Anticline Welborn and Smith, 1959).

WESTPOINT PROJECT

The Westpoint project (pl. 1, fig. 10, and table 2) in Tippecanoe County is owned by the Indiana Gas and Water Co. Storage is in an aquifer in Devonian limestone of the undifferentiated North Vernon and Jeffersonville section at a depth of 400 feet. Average thickness of the reservoir is 12 feet, and porosity is 8 percent. Entrapment is structural.

Twenty-seven wells are operated, thirteen for gas injection and extraction and fourteen for observation. Total storage capacity is 650,000 Mcf, and working storage capacity is 200,000 Mcf. Maximum daily deliverability is 7,500 Mcf.

Structural closure on the Devonian carbonate sequence at Westpoint, as at nearby Green Hill, is probably related to an underlying Silurian reef. Closure is much less, however, than that associated with Silurian pinnacle reefs to the south in Vigo, Sullivan, and Greene Counties. The Westpoint structure, which has closure of about 30 feet, does not have a pinnacle shape.

WILFRED PROJECT

The Wilfred project (pl. 1, fig. 10, and table 2) in Sullivan County is owned by the Texas Gas Transmission Corp. Storage is in the Geneva Dolomite (basal Devonian), from which oil was produced in commercial quantities. The storage reservoir is at a depth of 2,030 feet, is 30 feet thick, and has porosity of 12.3 percent and permeability of 84 millidarcies. Entrapment is in a reef structure which has 125 feet of closure on top of the Devonian carbonate sequence.

Eighteen wells are operated, thirteen for injection and extraction of gas and five for observation. Twenty-four old holes were cleaned out and plugged during development, and seven stratigraphic tests were drilled and plugged. Total storage capacity is 2,400,000 Mcf, working storage capacity is 1,200,000 Mcf, and maximum daily deliverability is 30,000 Mcf.

Structural and stratigraphic circumstances at Wilfred are essentially identical to those at Howesville and Linton, and the deliverability potential of individual wells in Wilfred is known to be extremely high. As at Howesville and Linton, the true permeability of the storage reservoir is probably many times the recorded permeability. Also, as at Howesville and Linton, the Silurian rocks which lie immediately below the Geneva probably have sufficient porosity and permeability to serve as an effective reservoir.

WORTHINGTON PROJECT

The Worthington project (pl. 1, fig. 10, and table 2) in Greene County is owned by the Citizens Gas and Coke Utility. Storage is in Devonian dolomite in the lower part of the undifferentiated North Vernon and Jeffersonville Limestones in a natural gas reservoir. The storage reservoir is at a depth of 1, 420 feet and is 35 feet thick. Porosity is 18. 1 percent, and permeability determinations of 18. 2 to 35. 4 millidarcies have been made. Entrapment is due to a reef structure.

Twenty- eight wells are operated, fourteen for observation and fourteen for gas injection and extraction. Total storage capacity is 9, 000, 000 Mcf.

Data on new wells drilled in Worthington have not been released by the operator. Four old holes in the southern part of the project are high structurally, however, and suggest structure of the pinnacle reef type.

As at Howesville, Linton, and Wilfred, effective reservoir permeability and effective reservoir thickness are probably greater than the recorded figures indicate.

GAS STORAGE POSSIBILITIES IN INDIANA.

PENNSYLVANIAN AND MISSISSIPPIAN SYSTEMS

Pennsylvanian, upper Mississippian (Chester), and middle Mississippian (Meramec) rocks are present in Indiana only in the Illinois Basin. Lower Mississippian rocks are present in both the Illinois and Michigan Basins. There are, however, only negligible occurrences of porous strata in the lower Mississippian of the Illinois Basin and no porous strata in the lower Mississippian of the Michigan Basin.

Since 1939 the Pennsylvanian, Chester, and Meramec of southwestern Indiana have been intensively explored for oil. The area explored includes Posey, Gibson, Vanderburgh, Warrick, Pike, Spencer, Perry, Dubois, Martin, Daviess, and Knox Counties (fig. 1). More than 250 oil fields and some gas fields have been found (figs. 11 and 12). Many of the oil fields are comprised of multiple reservoirs, and more than 500 oil res ervoirs have been discovered. Depth to the reservoirs ranges from a few hundred feet to approximately 3, 000 feet; area of the reservoirs ranges from less than a 100 acres to several hundred acres; and thickness of the reservoirs ranges from a few feet to as much as 30 to 40 feet (Carpenter and Smith, 1961).

As has been pointed out, porous strata abound in the Pennsylvanian and Chester and occur in the Meramec. Oil has been found in18 stratigraphic units of this rock section, and gas has been found in 14 (table 1). As has also been pointed out, compaction structures and stratigraphic traps are common in the Pennsylvanian and Chester. Stratigraphic traps also are present in the Meramec. Most of the oil that has been found in southwestern Indiana has accumulated in stratigraphic traps or compaction structures. Pronounced diastrophic structures in southwestern Indiana, as throughout Indiana, are not common. There are faults of appreciable displacement in Posey, Gibson, Spencer, and Perry Counties, but these have not played a significant role in the location of oil and gas accumulations.

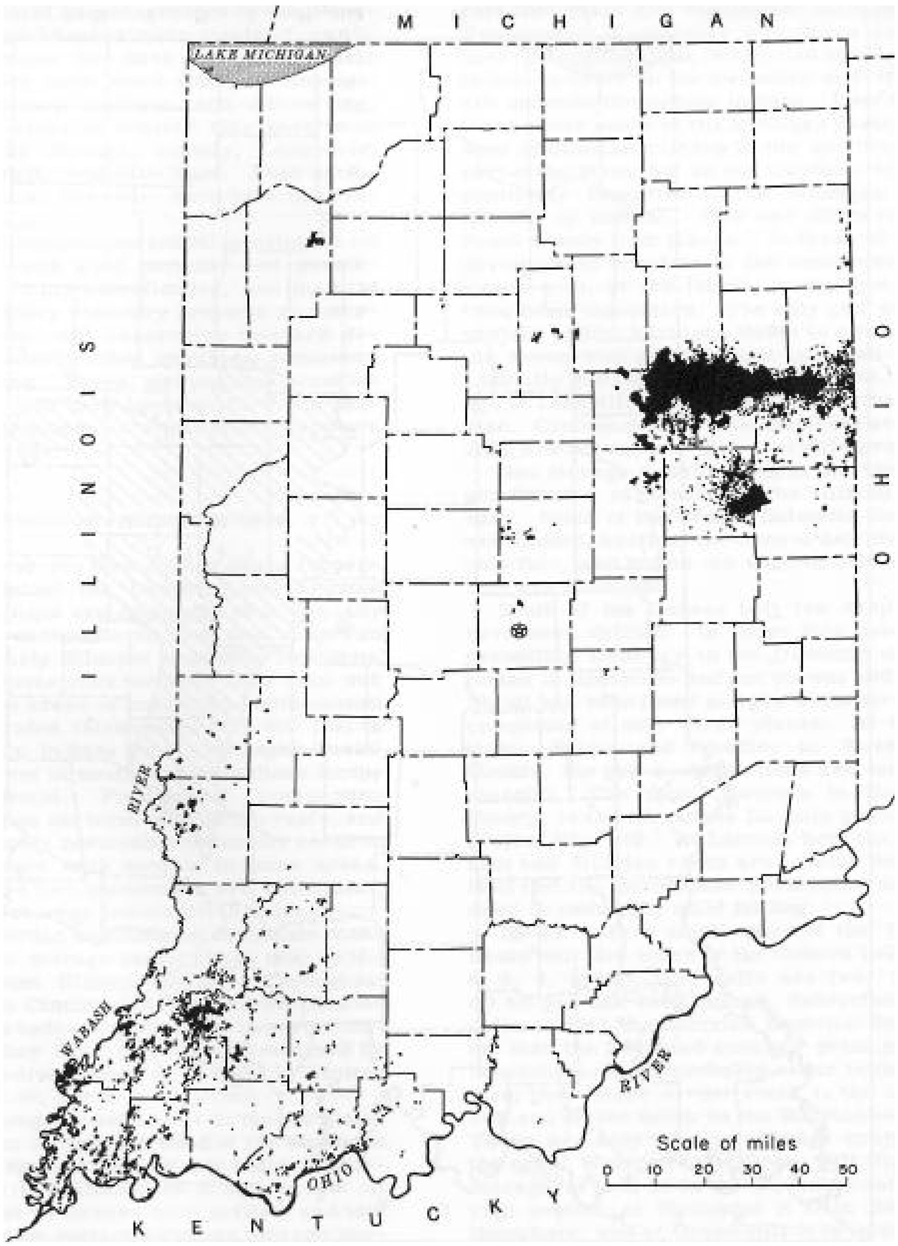

Figure ll.-Map of Indiana showing areas of oil production.

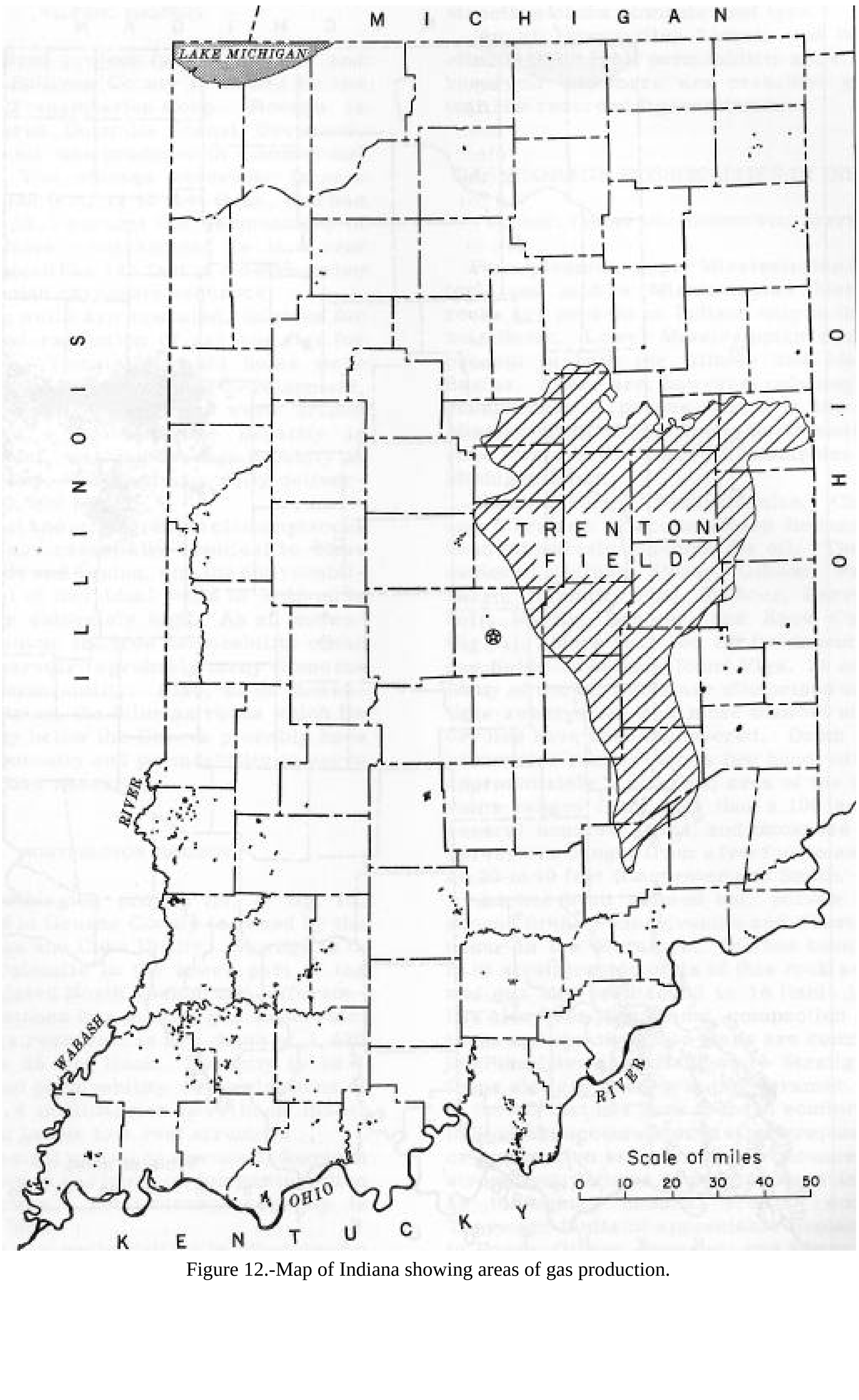

Figure 12.-Map of Indiana showing areas of gas production.

Most natural gas reservoirs in the Pennsylvanian and Mississippian strata of southwestern Indiana that have appreciable size have already been used for gas storage, namely, Oliver, Oaktown, and Alford (fig. 10). Also, some of limited size have been used for gas storage, namely, Loogootee, Glendale North, and Giro East. None of the oil reservoirs, however, have been used for gas storage.

Many Pennsylvanian and Mississippian oil reservoirs with good porosity and permeability are being waterflooded, and many of these secondary recovery projects are nearing depletion. Oil reservoirs that are depleted by waterflooding should be numerous in a few years. These, and perhaps some oil reservoirs that have been subjected to primary depletion only, offer excellent prospects for gas storage.

DEVONIAN AND SILURIAN SYSTEMS

Except for the New Albany Shale (uppermost Devonian) the Devonian and Silurian rocks of Indiana are composed of a virtually continuous carbonate section that ranges in age from early Silurian to middle Devonian. This carbonate rock section, less than 100 feet thick in areas of outcrop in southeastern Indiana, attains thicknesses of 1,000 feet in northeastern Indiana (in the Michigan Basin) and 1,350 feet in southwestern Indiana (in the Illinois Basin). Pronounced compaction structures, in the form of Silurian reefs, and also extremely permeable dolomites occur in this carbonate rock section in some areas. Where these two phenomena are coincident, unique gas storage possibilities exist.

The Devonian and Silurian carbonate rocks provide gas storage possibilities only in the Michigan and Illinois Basins. Throughout much of the Cincinnati Arch these carbonates do not have bedrock cover, and in part of that province they have been totally removed by erosion; bedrock cover is present in limited areas (fig. 4), but it is very thin.

Gas storage possibilities in the Devonian and Silurian carbonate rocks of the Michigan Basin are limited. Relatively little subsurface data are available for study, as few oil and gas test wells have been drilled, and this fact may color opinion as to gas storage possibilities. But subsurface data at hand, although indicating that there are some porous Devonian and Silurian dolomites, do not indicate that there are significant entrapments. Pronounced diastrophic structures are not known in the Michigan Basin, and stratigraphic entrapments in the Devonian and Silurian are unknown throughout Indiana. Reef structures occur south of the Michigan Basin in the area of Silurian outcrop in the north-central part of the State, but as yet they have not been positively identified in the Michigan Basin portion of Indiana. Gas and oil have been found at only four places. At three of these, development consists of the completion of a single well; at the fourth, seven gas wells have been completed. The only gas storage project in the Michigan Basin is adjacent to the seven-well gasfield and is known as the Linkville gas storage project (fig. 10). Storage at Linkville is to be effected in the Silurian. Circumstances of entrapment at Linkville are not clear. (See Linkville project.)

Gas storage possibilities in the Devonian and Silurian carbonates of the Illinois Basin vary. South of the Geneva Dolomite belt they are limited, north of the Geneva belt they are only fair, and within the Geneva belt (fig. 9) they are excellent.

South of the Geneva belt few deep wells have been drilled. In those that have, the prevailing lithology in the Devonian and Silurian is limestone and not porous dolomite. No oil has been found and gas wells have been completed at only three places. At two of these, Salem and Smedley in Washington County, the gas accumulations are noncommercial. The third, Laconia in Harrison County, is the site of the Laconia gas storage project (fig. 10). At Laconia both the Devonian and Silurian rocks are locally dolomitized and are porous and permeable; entrapment is caused by mild folding.

In the rather small part of the Illinois Basin that lies north of the Geneva belt (figs. 4, 5, 6, and 9). test wells are few, and no oil or gas has been found. Subsurface data indicate that the Silurian contains dolomite but that the Devonian consists principally of limestone. Reefs probably occur in the Silurian; they occur to the south in the Geneva belt and to the north in the Silurian outcrop. There are only two gas storage projects in the area, Westpoint and Green Hill (fig. 10). Storage at both is in the Devonian and Silurian section; at Westpoint it is in Devonian limestone, and at Green Hill it is in Silurian dolomite. Entrapment at both projects is caused by mild structural closure, which is believed to be related to Silurian reefs. The structural closures at Westpoint and Green Hill were outlined by exploratory drilling programs conducted by the Indiana Gas and Water Co. for the express purpose of determining sites favorable for gas storage. At both projects the storage reservoirs are aquifers.

Within the Geneva belt the Geneva Dolomite, the basal Devonian formation, and dolomites in the overlying undifferentiated North Vernon and Jeffersonville section have superior reservoir quality, and structural closures are relatively abundant. The structural closures are readily divisible into two groups, those that occur to the east along the Mt. Carmel Fault (fig. 13) and those that occur to the west in the pinnacle reef area (fig. 14).

The Mt. Carmel Fault is one of the few pronounced diastrophic structural features known in Indiana. Throughout its mapped extent it is paralleled to the west by a structural reversal designated as the Leesville Anticline (Melhorn and Smith, 1959). Domes of limited closure occur on the Leesville Anticline, and two of these (fig. 13) are the sites of gas storage projects. At Leesville in Lawrence County storage has been established in an aquifer in the Geneva Dolomite. AtUnionville in Monroe County storage has been established in the undifferentiated North Vernon and Jeffersonville section and in the underlying Geneva; the upper reservoir originally contained a commercial accumulation of gas, whereas the Geneva reservoir is an aquifer. Wherever structural closures occur along the Leesville Anticline within the Geneva belt, opportunities exist for establishing gas storage in Devonian dolomites.

Within the Devonian and Silurian carbonate section of Indiana, gas storage possibilities Are best in the western part of the Geneva belt. In this area there has been extensive drilling for Devonian oil, and abundant subsurface information has resulted. Gas storage possibilities are unique because highly permeable Devonian dolomites are coincident with pronounced Silurian reef structures (figs. 9 and 14).

The Geneva Dolomite is 30 to 50 feet thick in the reef -structure area. There is a second Devonian dolomite in this area in the lower part of the undifferentiated North Vernon and Jeffersonville Limestones, immediately above the Geneva; it is 30 to 40 feet thick. Both dolomites are vuggy, and their high permeability is believed to be directly related to this vuggy characteristic.

The pinnacle- shaped Silurian reefs are not restricted to the area shown in figure 14. A few are known to the south in Daviess - and Dubois Counties, but these are outside the Geneva belt. Structural closure on beds overlying the reefs is a result of differential compaction in the Silurian- -differential compaction between the reefs and the muds deposited adjacent to the reefs. Some closure exists in all beds overlying the reefs but is greatest in the beds immediately overlying the reefs. Closure characteristically is abrupt. Characteristically, too, it is pronounced, commonly being about 100 to 125 feet on top of the Devonian carbonate rocks, some 130 to 170 feet above the reefs. (Reef structure as used in this paper refers to the draped structure induced on strata above a reef and not to the reef itself.)

Prolific oil production has been obtained from Devonian beds in many reef structures of Sullivan and Vigo Counties, and some oil production has been obtained from some reef structures in Clay and Vermillion Counties. In the reef structures of Greene and Owen Counties, with one exception, only gas has been found.

Gas storage has been established in five of the pinnacle reef structures (figs. 10 and 14). At Wilfred storage is in the Geneva Dolomite, which was originally an oil reservoir. At Howesville, Linton, Lonetree, and Worthington the storage reservoirs are all in the lower part of the undifferentiated North Vernon and Jeffersonville section, and all originally contained accumulations of natural gas. Structural closure on top of the Devonian limestone section at Wilfred is 125 feet; at Howesville it is 85 feet; at Linton it is 130 feet; at Lonetree it is 60 feet; and at Worthington it is estimated to be about 100 feet. Three of these projects- -Wilfred, Howesville, and Worthington- -are in operation, and a fourth, Linton, is being placed in operation. The combined storage capacity of these four projects is nearly 20 billion cubic feet, only slightly less than half of the total developed storage capacity in Indiana. Reef structures of west-central Indiana that have not been utilized (fig. 14) offer excellent opportunities for developing new gas storage projects.

The reef-structure storage is very probably the best type of storage in Indiana. It has two meritorious aspects. These are relatively large storage capacity with limited areal extent and high deliverability. The large storage capacity is due to the combina-

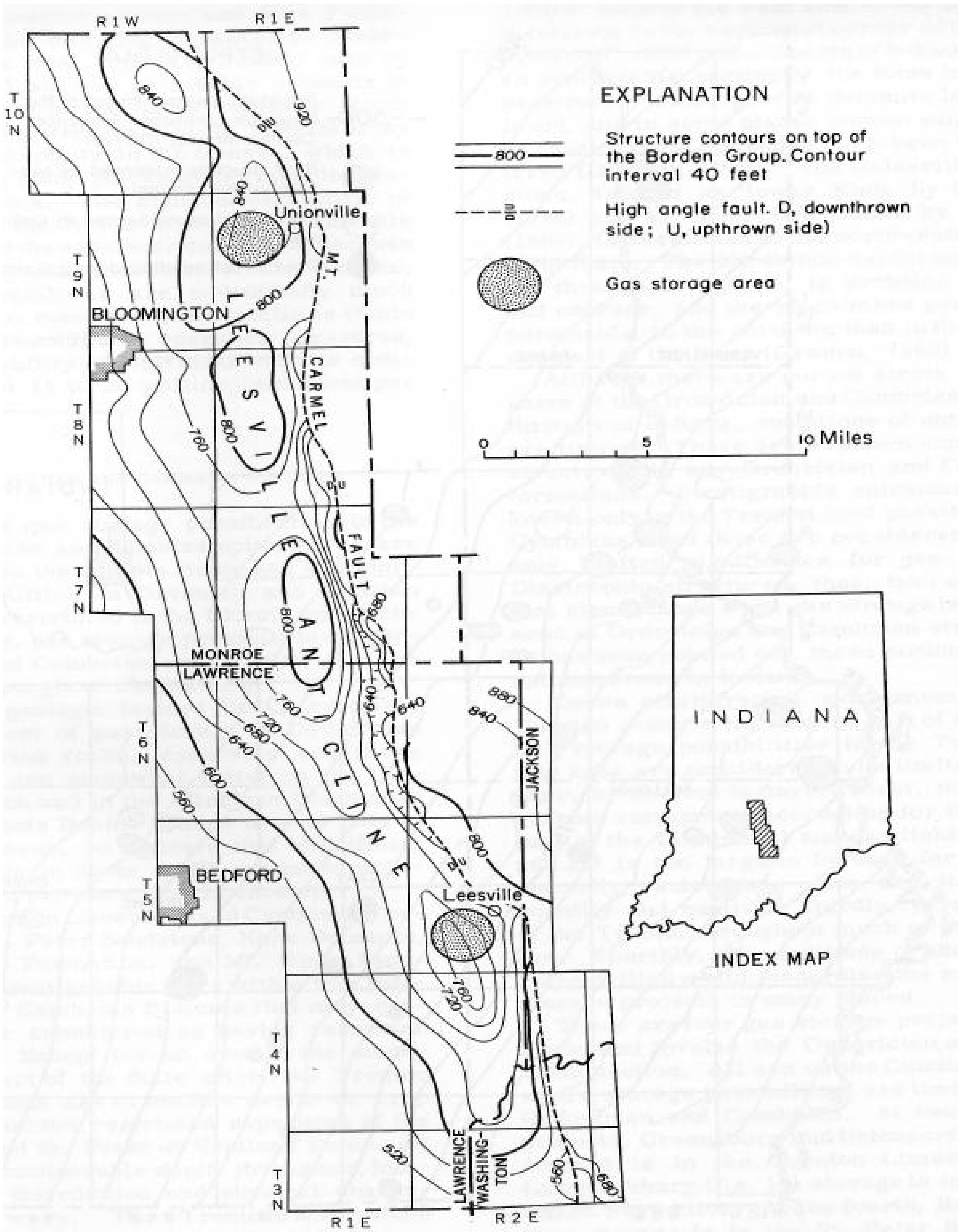

Figure 13.-Map showing structure of Mt. Carmel Fault region, south-central Indiana. Modified after Melhorn and Smith, 1959.

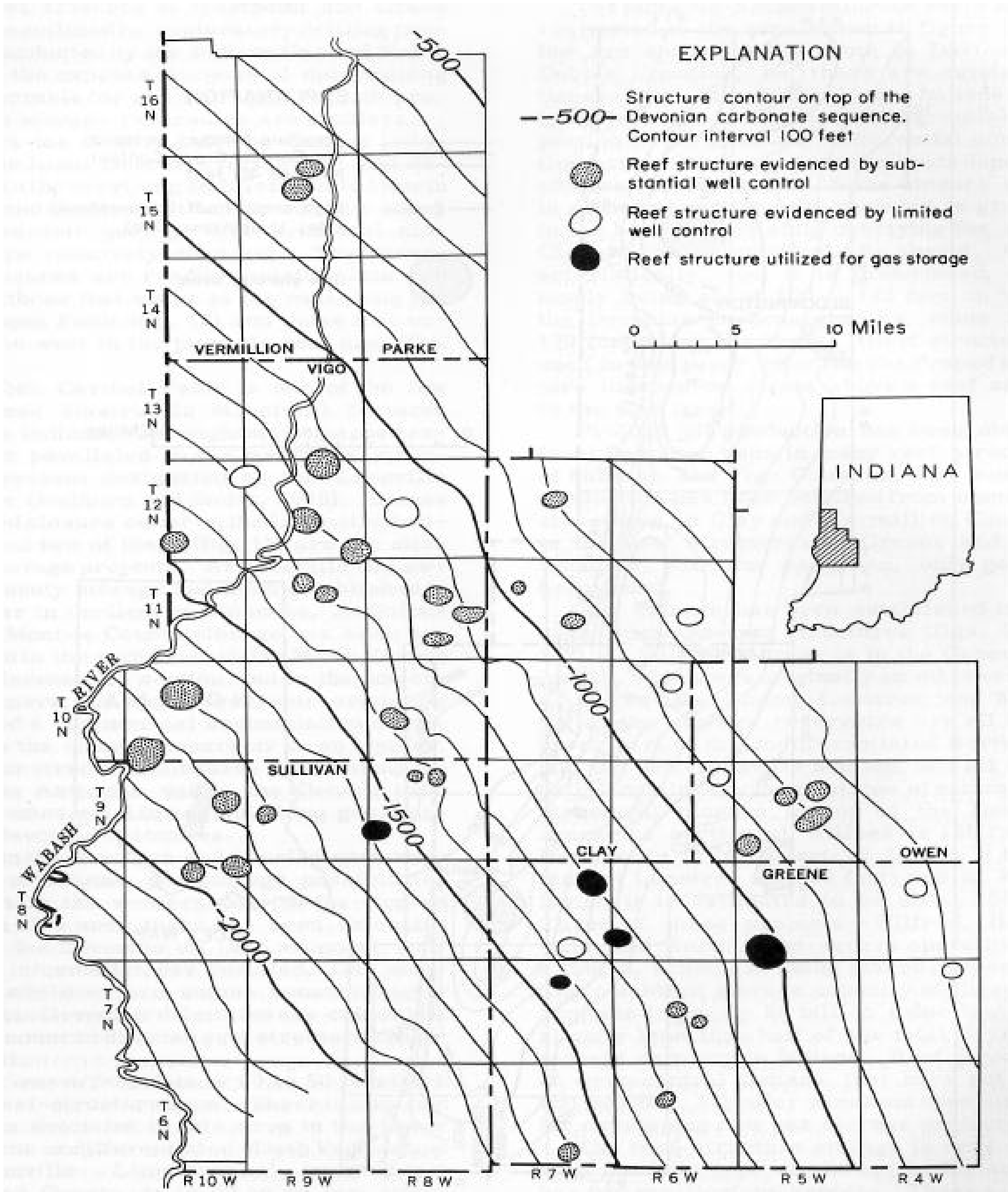

Figure 14.-Map showing location of reef structures in west~central Indiana.

tion of pronounced closure and thick reservoir beds; the effective thickness of reservoirs is, in fact, probably limited only by structural closure as permeable dolomite in the lower part of the undifferentiated North Vernon and Jeffersonville is underlain by permeable dolomite in the Geneva, which is underlain in many places by permeable Silurian reef rock. The high deliverability, of course, is due to the unusually permeable character of the reservoir dolomites; because of the vuggy characteristic of these rocks, true permeabilities are undoubtedly much greater than recorded permeabilities (table 2). With reservoirs at operating pressures, the deliverability of individual wells is commonly about 15 to 20 million cubic feet per day.

ORDOVICIAN AND CAMBRIAN SYSTEMS

Whereas gas storage possibilities in the Pennsylvanian and Mississippian rocks are restricted to the Illinois Basin and gas storage possibilities in Devonian and Silurian rocks are restricted to the Illinois and Michigan Basins, gas storage possibilities in Ordovician and Cambrian rocks exist, to some degree, throughout the State.

As for geologic factors that bear on the establishment of gas storage in Ordovician and Cambrian rocks, reservoir conditions in general are somewhat better on the Cincinnati Arch and in the Michigan Basin than in the Illinois Basin. There are no data at hand, however, to indicate that significant entrapments in these rocks are more prevalent in one province than in another.

The Trenton Limestone and Cynthiana Formation, St. Peter Sandstone, Knox Dolomite, Eau Claire Formation, and Mt. Simon Sandstone are stratigraphic units within the Ordovician and Cambrian Systems that may reasonably be considered as having reservoir potential. Except for an area in the southeastern part of the State where the Trenton and Cynthiana are at shallow depth, or crop out, and for the restricted exposures of the Trenton and St. Peter at Kentland Dome, all occur at considerable depth throughout Indiana. But distribution and physical characteristics vary. The Trenton Limestone grades from limestone in southern Indiana to dolomite in northern Indiana (Gutstadt, 1958) with attendant improvement in porosity and permeability. The St. Peter is restricted as a sheet sand to the west side of the State and is thickest inthe northwest corner of the State (Gutstadt, 1958). In all parts of Indiana where an appreciable section of the Knox has been penetrated, some porous dolomite has been found, and in some places porous sandstones of considerable thickness have been encountered (Dawson, 1960). The Galesville Sandstone, treated as lower Knox by Gutstadt (1958) and as upper Eau Claire by Dawson (1960), is restricted to the northwestern part of the State. The Mt. Simon Sandstone, present throughout Indiana, is probably cleaner and coarser, and therefore more porous and permeable, in the northern than in the southern part of the State (Dawson, 1960).

Although there are porous strata in some parts of the Ordovician and Cambrian section throughout Indiana, conditions of entrapment are limited. There are no known compaction structures in any Ordovician and Cambrian formations. Stratigraphic entrapments are known only in the Trenton (and possibly in the Cynthiana), and these are considered to be of only limited significance for gas storage. Diastrophic structures, thus, take on a special significance when gas storage is considered in Ordovician and Cambrian strata, and as has been pointed out, these structures are not numerous in Indiana.

Known stratigraphic entrapments in the Trenton occur in the eastern part of the State. Gas storage possibilities in the Trenton in this area are considered to be limited, however, by several factors. First, the stratigraphic entrapment accounting for the major part of the Trenton oil and gas field (figs. 11 and 12) is too large to be used for storage. Secondly, subsurface data are limited in quantity and quality. Thirdly, permeability of the Trenton throughout much of the area is low. Fourthly, the multitude of unrecorded holes drilled would jeopardize the success of storage projects in many places.

There are four gas storage projects in Indiana that involve the Ordovician and Cambrian section. All are on the Cincinnati Arch where storage possibilities are limited to the Ordovician and Cambrian. At two of these projects, Greensburg and Unionport (fig. 10), storage is in the Trenton Limestone. At Lawrenceburg (fig. 10) storage is in the Cynthiana Formation. At the fourth, Royal Center, storage is in the St. Peter Sandstone. At the Greensburg project entrapment is stratigraphic, at the Lawrenceburg and Unionport projects entrapment is presumably stratigraphic, and at the Royal Center project entrapment is structural. The Greensburg, Lawrenceburg, and Unionport projects are limited in quality because of reservoir characteristics. At Royal Center the reservoir characteristics of the St. Peter are very good, and rated capacity is the largest of any storage project in Indiana. At Greensburg, Lawrenceburg, and Unionport the storage reservoirs originally contained accumulations of natural gas, but at Royal Center the storage reservoir is an aquifer.

Diastrophic structures are the key to establishing effective gas storage in the Ordovician and Cambrian of Indiana. Where these features exist multiple storage reservoirs probably can be developed; for example, at Royal Center (pl. 1) storage very likely can be effected in the Knox, Galesville, and Mt. Simon, in addition to that in the St. Peter; and on the Leesville Anticline (fig. 13) storage very likely can be developed in the Knox, particularly in the large sandstone body occurring within the Knox, and in the Mt. Simon. Delineation of diastrophic structures in the Ordovician and Cambrian, however, entails considerable costs. Geophysics or stratigraphic drilling, or both, must be employed. The pronounced diastrophic structure at Royal Center was delineated by an extensive exploratory drilling program conducted by the Northern Indiana Public Service Co.

CONCLUSIONS

Developed underground gas storage capacity in Indiana is relatively small. Gas storage projects have been established at an increased tempo in recent years, however, and currently aggressive programs are being conducted for the establishment of additional storage sites. Storage capacity will be increased materially in the years immediately ahead.

Because of basic geologic factors and available subsurface information, gas storage can be effected in the Illinois Basin much easier than in other parts of Indiana. Storage possibilities are very good in rocks of the Pennsylvanian and Mississippian Systems. In these rocks, which are restricted to the Illinois Basin, porous strata abound and compaction structures and stratigraphic entrapments-are very common.

Within the Devonian and Silurian carbonate sequence, storage possibilities are excellent in the Geneva Dolomite belt. This east-west oriented belt in which extremely permeable dolomites are present is restricted to part of the Illinois Basin. Where structural closures occur in this belt, gas storage can be effected, and where pinnacle reef structures occur in this belt in west-central Indiana, storage possibilities are unique.

Some permeable strata are present at depth in the Ordovician and Cambrian rock section throughout the State. Known significant entrapments in this rock section, however, are few. There are no known compaction structures, and known stratigraphic entrapments are limited to the Trenton Limestone in areas where permeability is frequently low. Diastrophic structures, thus, are of particular significance to the establishment of gas storage in Ordovician or Cambrian rocks, and these structures are not numerous in Indiana.

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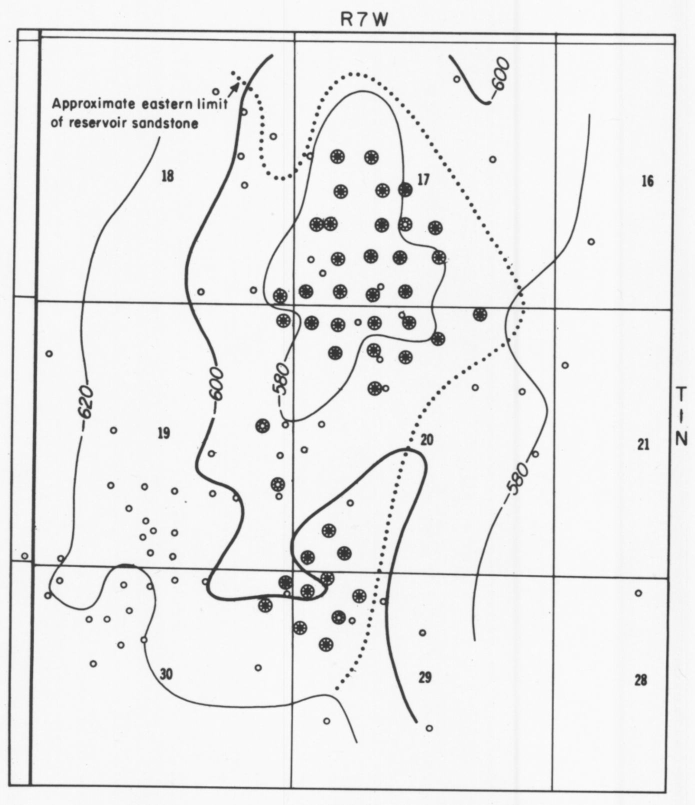
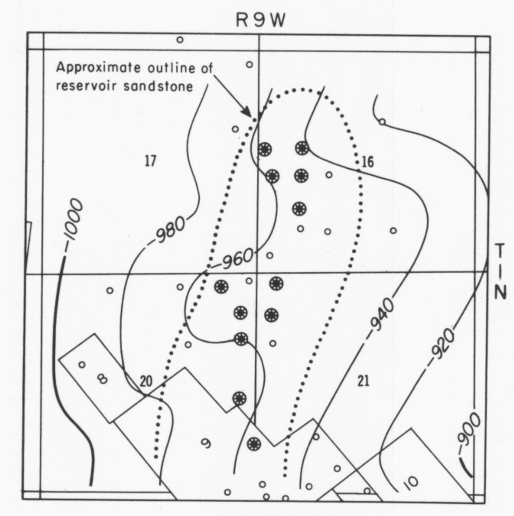


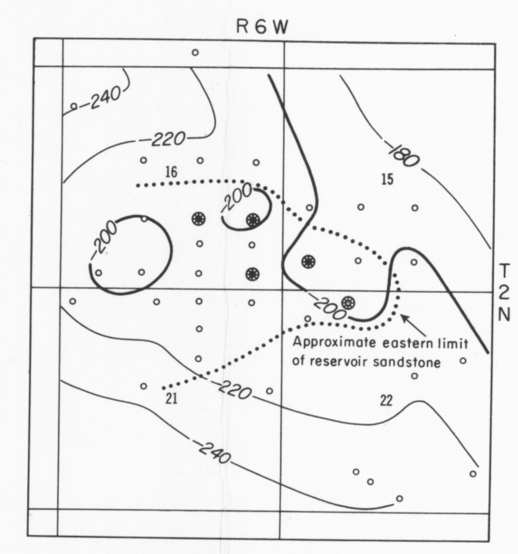
ALFORD

Structure contours on top of the Cypress Formation; contour interval 20 ft. Storage reservoir is approximately 15 ft below contoured horizon.



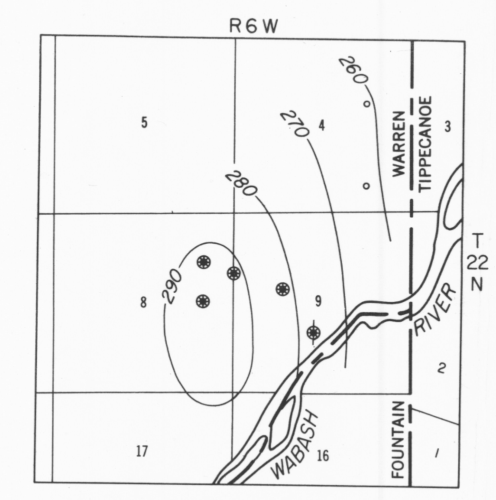
GIRO EAST

Structure contours on top of the Cypress Formation; contour interval 20 ft. Storage reservoir is approximately 10 ft below contoured horizon.



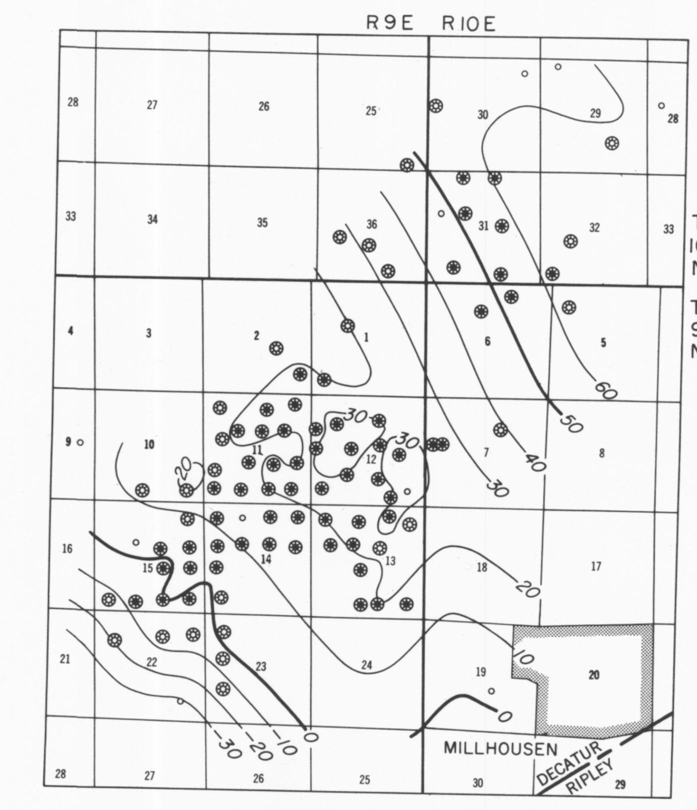
GLENDALE NORTH

Structure contours on top of the Cypress Formation; contour interval 20 ft. Storage reservoir is approximately 10 ft below contoured horizon.



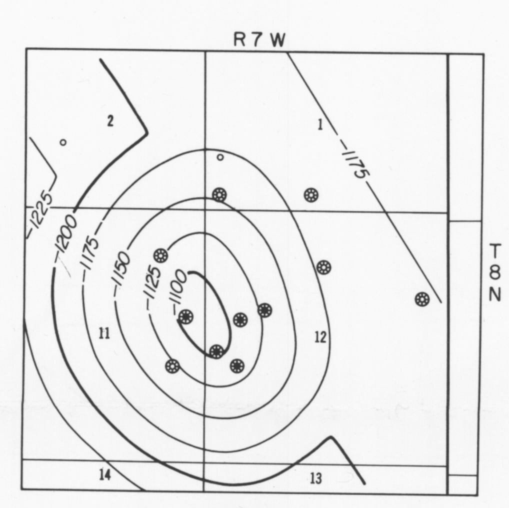
GREEN HILL

Structure contours on top of the Devonian carbonate sequence; contour interval 10 ft. Storage reservoir is approximately 55 ft below contoured horizon.



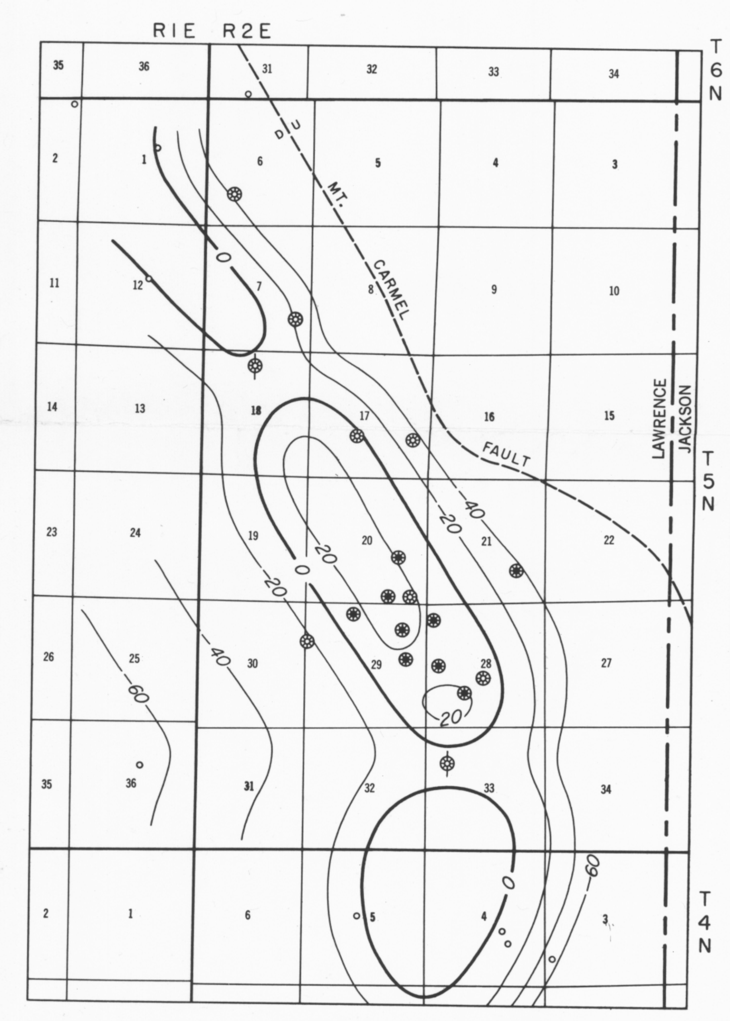
GREENSBURG

Structure contours on top of the Trenton Limestone; contour interval 10 ft. Top of storage reservoir and contoured horizon are coincident.



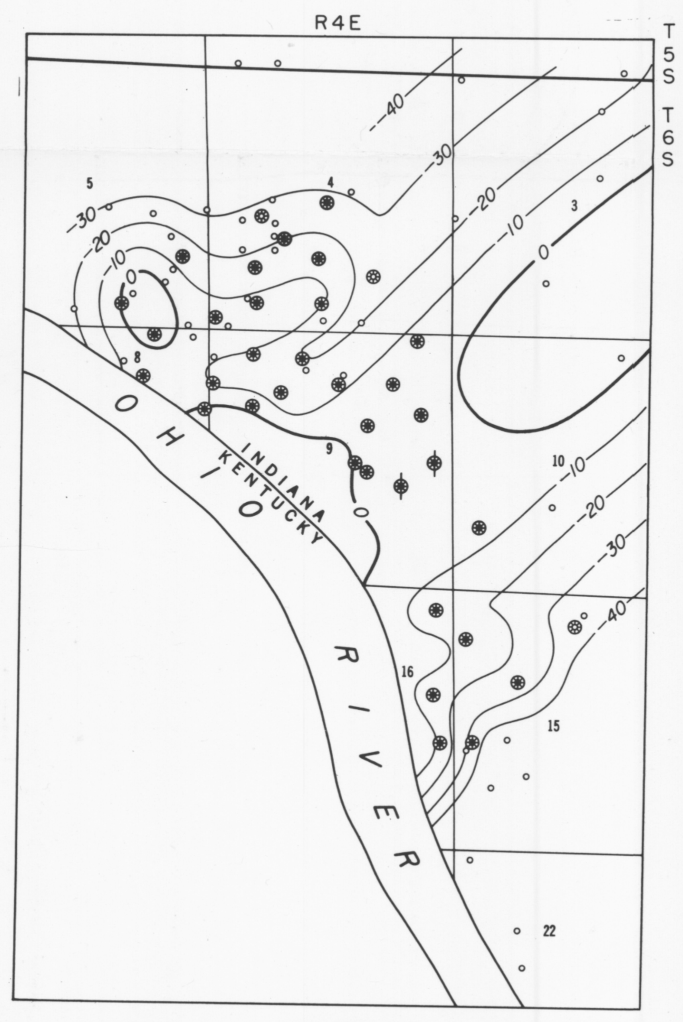
HOWESVILLE

Structure contours on top of the Devonian carbonate sequence; contour interval 25 ft. Storage reservoir is approximately 65 ft below contoured horizon.



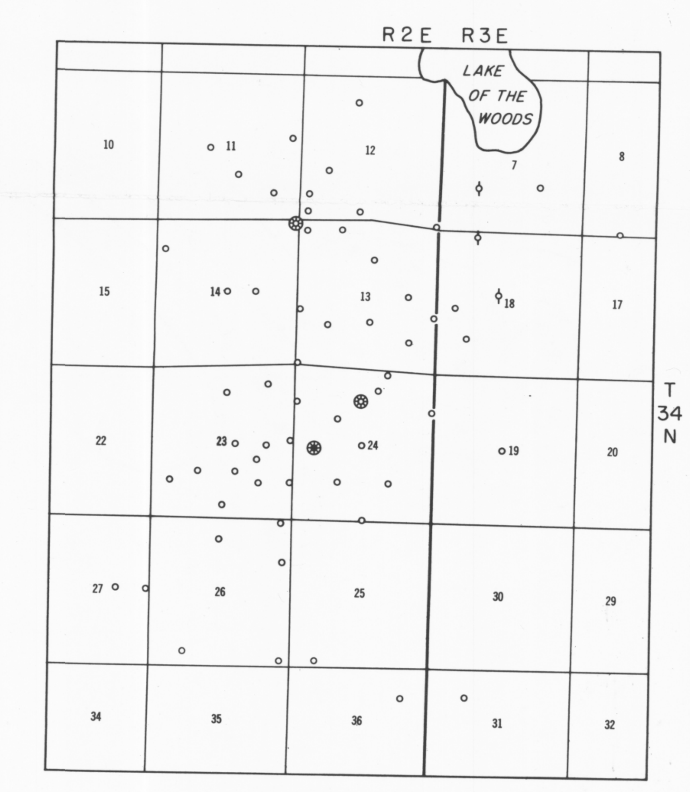
LEESVILLE

Structure contours on top of the Devonian carbonate sequence; contour interval 20 ft. Storage reservoir is approximately 90 ft below contoured horizon.



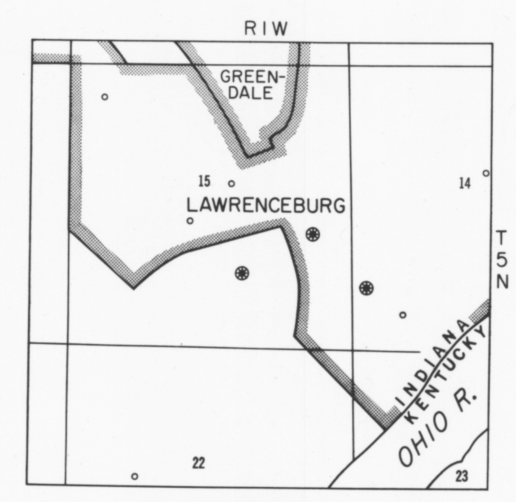
LACONIA

Structure contours on top of the Devonian carbonate sequence; contour interval 10 ft. Top of storage reservoir and contoured horizon are coincident.



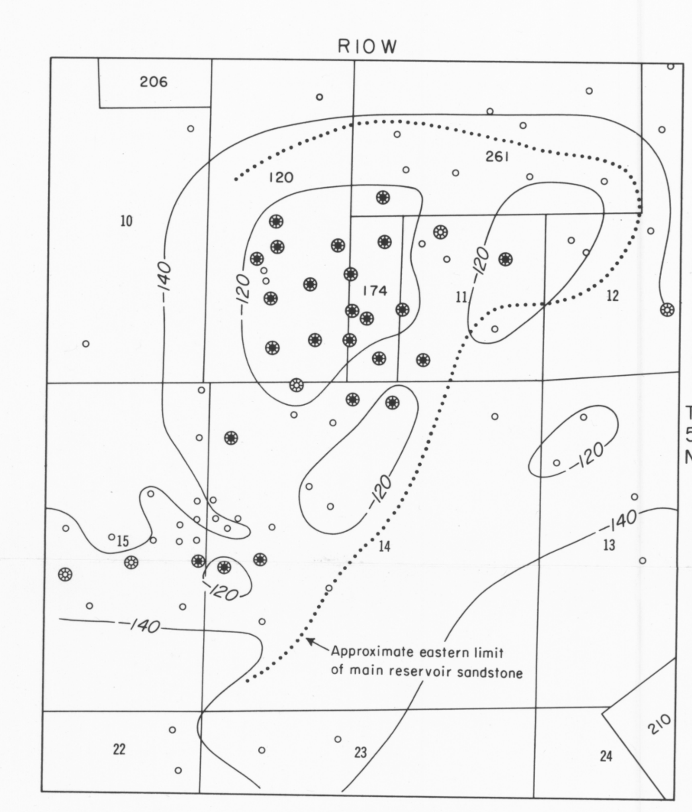
LINKVILLE

Geologic interpretation omitted because most well data are confidential.



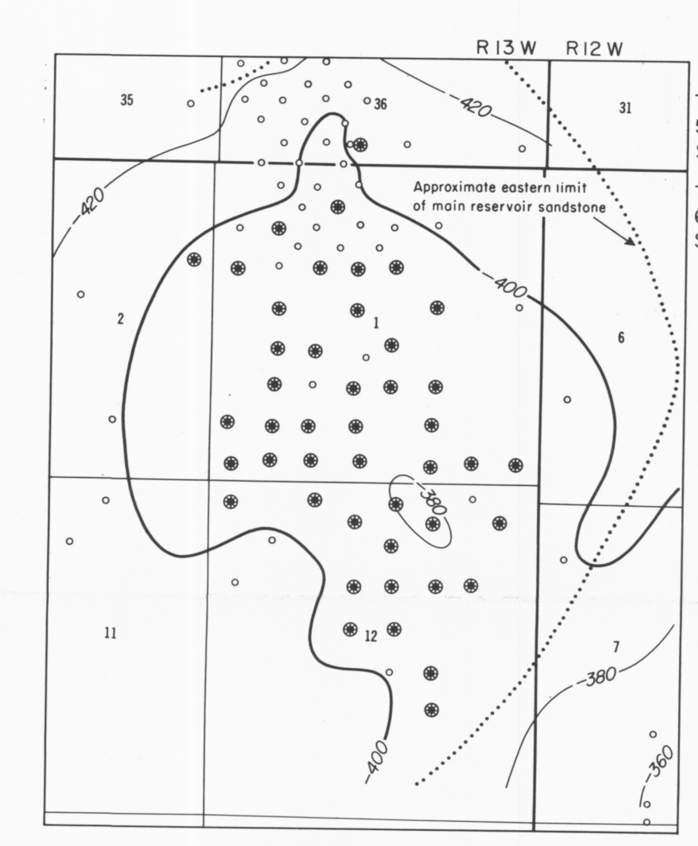
LAWRENCEBURG

Geologic interpretation omitted because of insufficient well data.



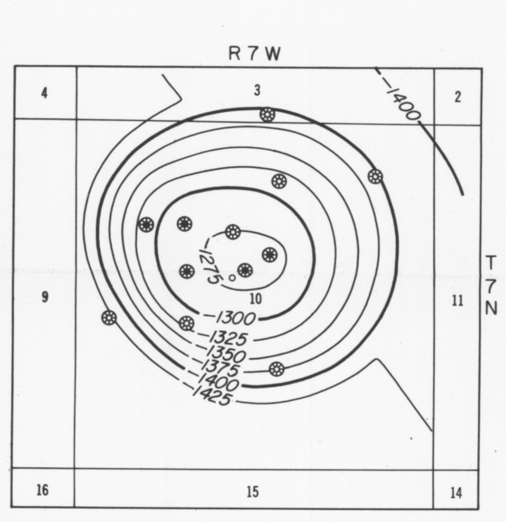
OAKTOWN

Structure contours on top of Coal III; contour interval 20 ft. Main storage reservoir is approximately 55 ft below contoured horizon.



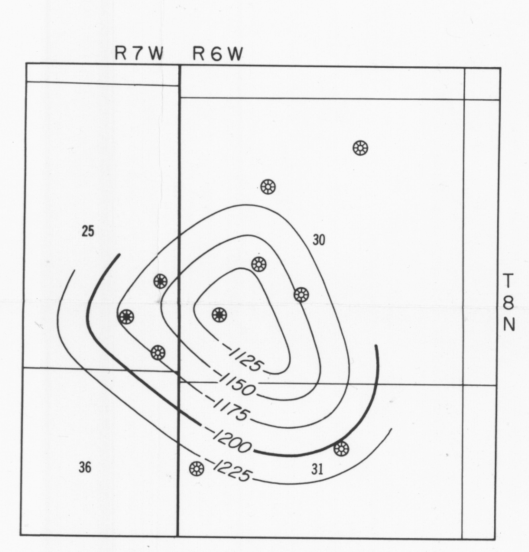
OLIVER

Structure contours on top of Coal III; contour interval 20 ft. Main storage reservoir is approximately 15 ft below contoured horizon.



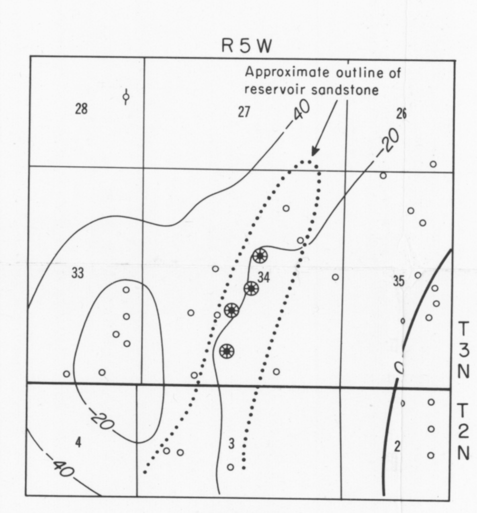
LINTON

Structure contours on top of the Devonian carbonate sequence; contour interval 25 ft. Storage reservoir is approximately 70 ft below contoured horizon.



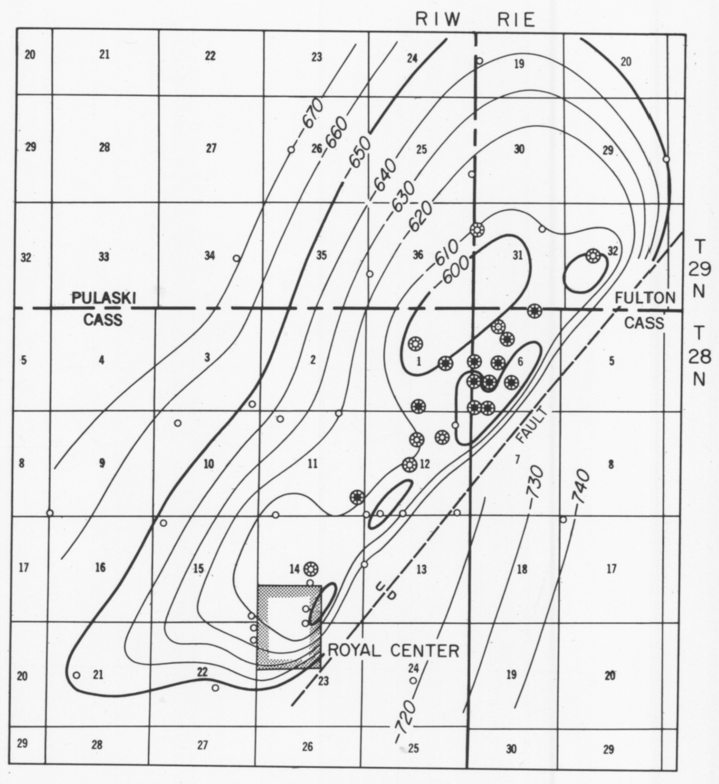
LONETREE

Structure contours on top of the Devonian carbonate sequence; contour interval 25 ft. Storage reservoir is approximately 70 ft below contoured horizon.



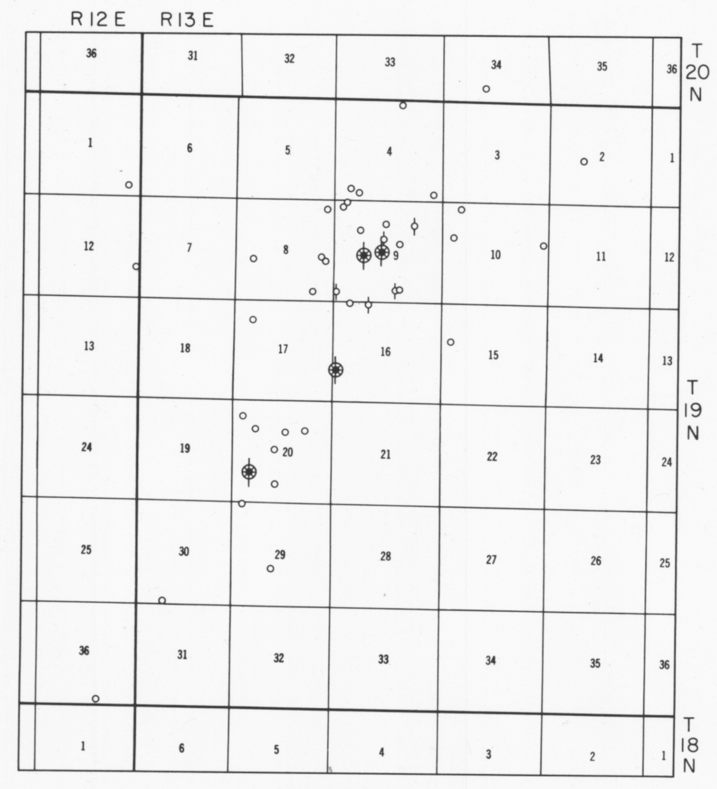
LOOGOOTEE

Structure contours on top of the Bethel Formation; contour interval 20 ft. Storage reservoir is approximately 10 ft below contoured horizon.



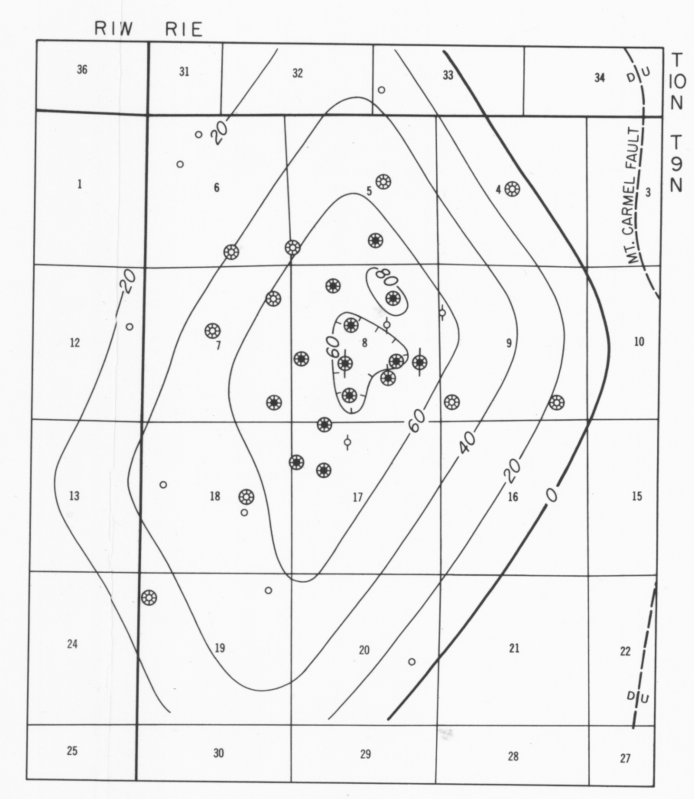
ROYAL CENTER

Structure contours on top of the St. Peter Sandstone; contoured interval 10 ft. Top of storage reservoir and contoured horizon are coincident.



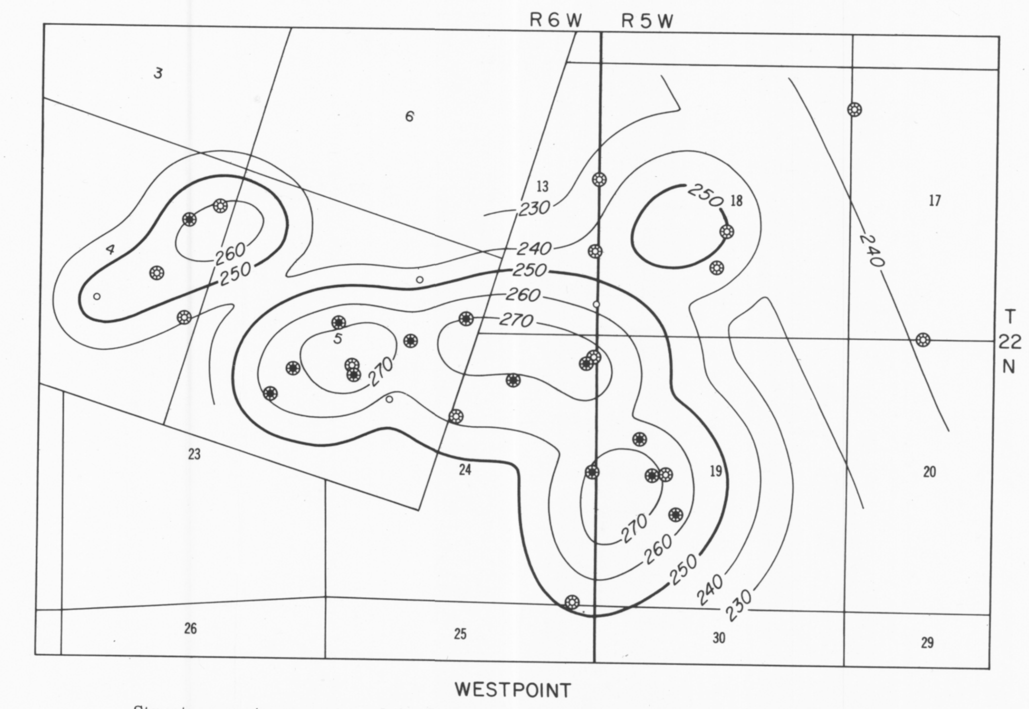
UNIONPORT

Geologic interpretation omitted because most well data are confidential.



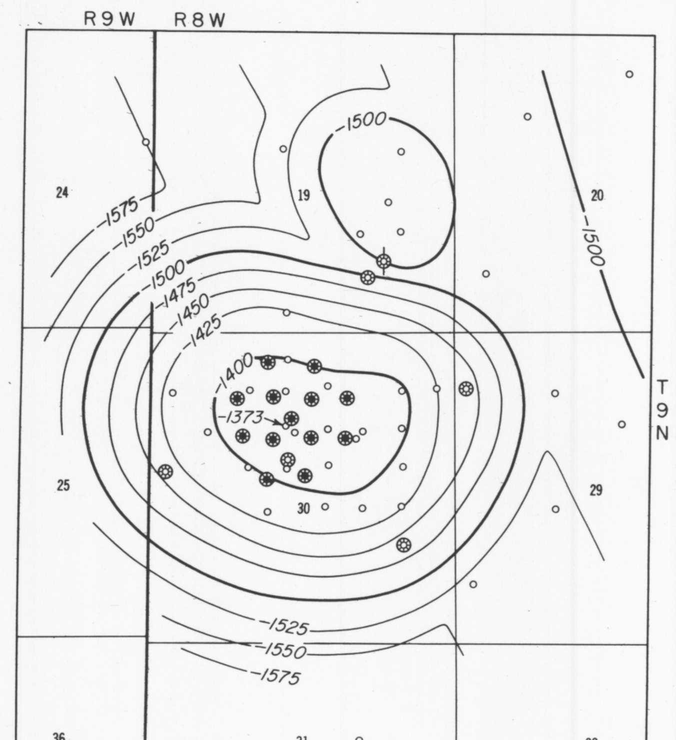
UNIONVILLE

Structure contours on top of the Devonian carbonate sequence; contour interval 20 ft. Top of upper storage reservoir and contoured horizon are coincident; lower storage reservoir is approximately 90 ft below contoured horizon.



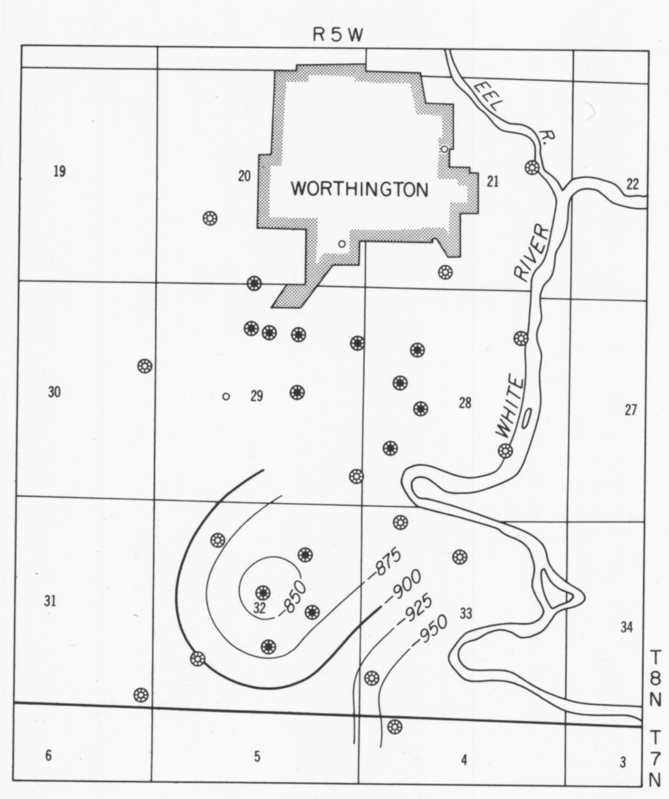
WESTPOINT

Structure contours on top of the Devonian carbonate sequence; contour interval 10 ft. Storage reservoir is approximately 20 ft below contoured horizon.



WILFRED

Structure contours on top of the Devonian carbonate sequence; contour interval 25 ft. Storage reservoir is approximate 115 ft below contoured horizon.



WORTHINGTON

Structure contours on top of the Devonian carbonate sequence; contour interval 25 ft. Storage reservoir is approximately 70 ft below contoured horizon. Geologic interpretation incomplete because much of the well data is confidential.

EXPLANATION

COMPLETED WELLS
- Gas storage well, injection and extraction
- Gas storage well, observation
- Other well

PLANNED WELLS
- Gas storage well, injection and extraction
- Gas storage well, observation
- Other well

The scale of each project map is indicated by section lines. The sides of all normal sections are approximately 1 mile in length.

Datum is mean sea level.

INDEX MAP SHOWING LOCATION OF GAS STORAGE PROJECTS

MAPS OF GAS STORAGE PROJECTS IN INDIANA

Compilation complete to October 10, 1961.
Drafted by John E. Peace and Betty Marzan

By T. A. Dawson and G. L. Carpenter

1963